A Reconnaissance Natural Hazard Assessment of Lakes Lyndon, Coleridge and Tekapo

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Frontispiece: The Lake Tekapo Township.

ABSTRACT

The Canterbury Region is susceptible to a variety of natural hazards, including earthquakes, landslides and climate hazards. Increasing population and tourism within the region is driving development pressures and as more and more development occurs, the risk from natural hazards increases. In order to avoid development occurring in unacceptably vulnerable locations, natural hazard assessments are required. This study is a reconnaissance natural hazard assessment of Lakes Lyndon, Coleridge and Tekapo.

There is restricted potential for development at Lake Lyndon, because the land surrounding the lake is owned by the Crown and has a number of development restrictions. However, there is the potential for conservation or recreation-linked development to occur. There is more potential for development at Lake Coleridge. Most of the land surrounding the lake is privately owned and has less development restrictions. The majority of land surrounding Lake Tekapo is divided into Crown-owned pastoral leases, which are protected from development, such as subdivision. However, there are substantial areas around the lake, which are privately owned and, therefore, have potential for development.

Earthquake, landslide and climate hazards are the main natural hazards threatening Lakes Lyndon, Coleridge and Tekapo. The lakes are situated in a zone of active earth deformation in which large and relatively frequent earthquakes are produced. A large number of active faults lie within 15 km of each lake, which are capable of producing M7 or larger earthquakes. Ground shaking, liquefaction, landslides, tsunami and seiches are among the consequences of earthquakes, all of which have the potential to cause severe damage to lives, lifelines and infrastructure. Landslides are also common in the landscape surrounding the lakes. The majority of slopes surrounding the lakes are at significant risk from earthquake-induced failure under moderate to strong earthquake shaking. This level of shaking is expected to occur in any 50 year period around Lakes Lyndon and Coleridge, and in any 150 year period around Lake Tekapo. Injuries, fatalities and property damage can occur directly from landslide impact or from indirect effects such as flooding from landslide-generated tsunami or from landslide dam outbreaks. Lakes Lyndon, Coleridge and Tekapo are also susceptible to climate hazards, such as high winds, drought, heavy snowfall and heavy rainfall, which can lead to landslides and flooding. Future climate change due to global warming is most likely going to affect patterns of frequency and magnitudes of extreme weather events, leading to an increase in climate hazards.

Before development is permitted around the lakes, it is essential that each of these hazards is considered so that unacceptably vulnerable areas can be avoided.

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CHAPTER 1 -
INTRODUCTION

1.1 Project Introduction

The lakes of inland Canterbury have long been recognised as ideal sites for development and are becoming increasingly popular as holiday destinations. However, to date, development around the lakes has been largely left unchecked with respect to natural hazards and is often sited in vulnerable areas. Like many other parts of New Zealand, Canterbury is subject to serious natural hazards, including earthquakes, landslides and climate hazards. In order to avoid future development occurring in unacceptably vulnerable areas, natural hazard assessments of each of the lake areas are required. This study aims to produce a reconnaissance natural hazard assessment of Lakes Lyndon, Coleridge and Tekapo and their immediate environs. It is intended to be useful for future developers, council bodies, residents and tourists. An understanding of both the physical and social environments of the lake areas is needed in order to achieve this aim.

1.2 Location of study areas

Lakes Lyndon, Coleridge and Tekapo are situated in the eastern Southern Alps in the central South Island, New Zealand (Figure 1.1). Lakes Lyndon and Coleridge lie within approximately 20 km of each other in central Canterbury, and Lake Tekapo lies approximately 100 km south-west of these lakes in south Canterbury. This study considers the areas immediately surrounding the lakes, with particular consideration to areas of potential future development.

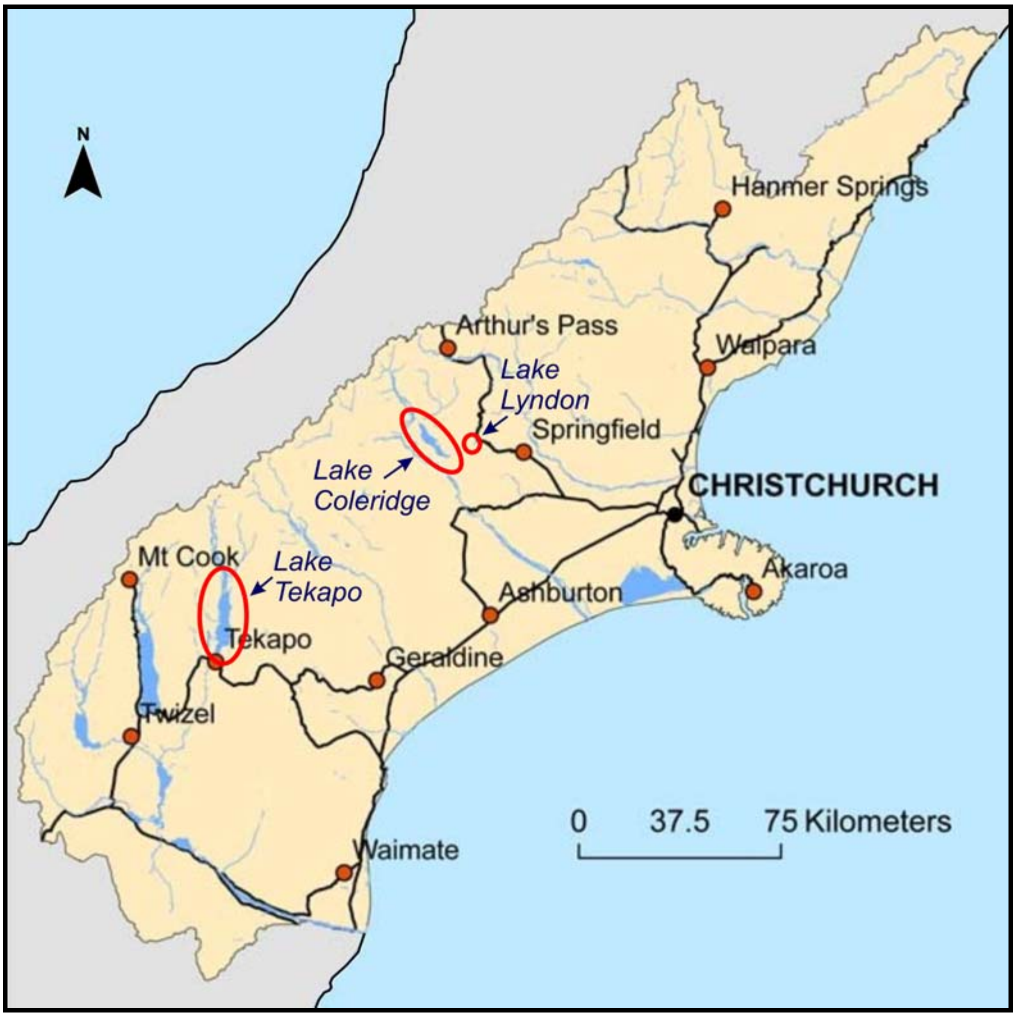

Figure 1.1: The location of Lakes Lyndon, Coleridge and Tekapo in Canterbury, New Zealand. Modified from www.bush.org.nz

1.3 Causes of Natural Hazards

In a natural system unmodified by humans, natural processes, such as earthquakes, flooding and landslides, occur without any threat to human life. A problem does not exist until humans modify these natural systems by occupying and developing areas, and consequently introducing an element of danger to themselves. Natural hazards arise from introduced human assets being susceptible to damage from natural processes. The natural and social aspects of a natural hazard/disaster cannot therefore be separated from each other and must be equally emphasised (Wisner, 2004). There are three main reasons why people place themselves in vulnerable positions:

1. Development pressure can force people to occupy ‘unsafe’ areas.
2. Sometimes the danger is not recognised.
3. People and organisations can be reluctant to acknowledge that there is a problem.

The major natural processes that occur in New Zealand, such as earthquakes, volcanic activity, slope instability and climatic processes, are all consequences of New Zealand’s relationship with the Australian and Pacific plate boundary zone, and with the active weather systems of the southern mid-latitudes (Hicks & Campbell, 1998). Due to New Zealand’s long, narrow and mountainous landscape, there are hardly any areas that are not continually modified by natural processes. Because of New Zealand’s increasing population, and population and tourism trends driving development pressure, it is becoming imperative to identify hazardous natural processes in order to protect both natural and human systems.

1.4 New Zealand’s Tectonic Setting

The landscapes of New Zealand are continually changing. This dynamic nature is primarily due to New Zealand’s location across the Australian and Pacific plate boundary, which runs diagonally across the country (Figure 1.2). The outer 100 km of the earth, the crust, is divided into eight large rigid slabs of rock, or “tectonic plates”, and five smaller ones (Aitken, 1999). These interlocking plates are constantly moving in relation to each other but at varying rates and in varying directions (Hicks & Campbell, 1998). At or near the boundaries between these plates most of the world’s volcanism, earthquakes and surface deformation exist (Aitken, 1999). Therefore the active boundary between the Australian and Pacific plates, which runs directly through New Zealand, is of great significance to this study.

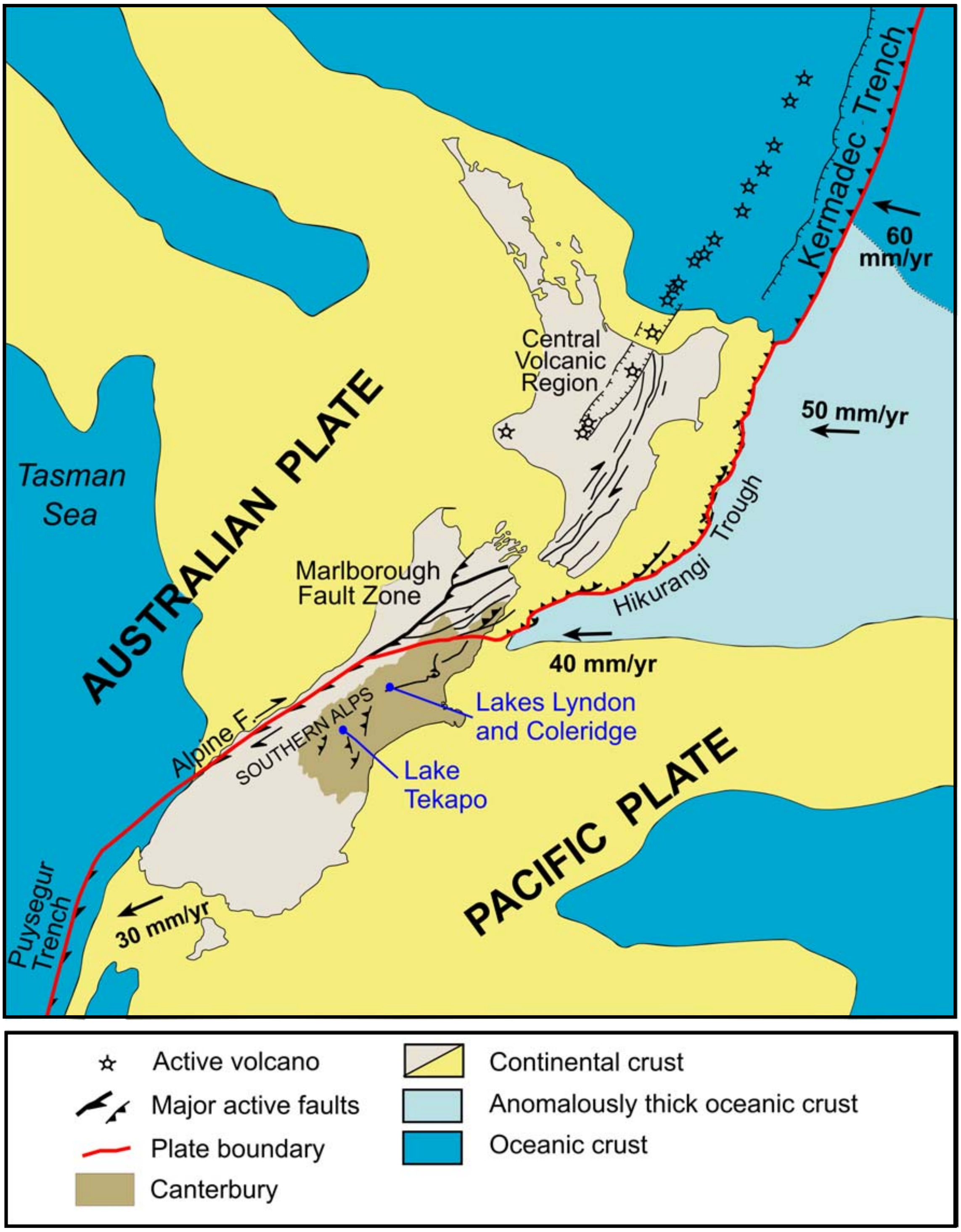

Figure 1.2: The tectonic setting and main structural features of the New Zealand micro-continent straddling the obliquely convergent Australia-Pacific plate boundary zone. Numbered arrows show rates of relative convergence in mm per year. Modified from Pettinga *et al.*, (2001): 285.

The crust at plate boundaries behaves in different ways depending on the crustal properties and nature of relative plate motion. The Australian and Pacific plates are converging and this convergence is accommodated in three different ways along the length of New Zealand (Reyners & Cowan, 1993). From the East Cape to Marlborough, the Pacific plate is being subducted or driven beneath the Australian Plate (Hicks & Campbell, 1998). A transition from subduction to continental collision then occurs in north Canterbury and this type of relationship dominates the South Island from Kaikoura to Milford Sound (Aitken, 1999). South of Milford, the Australian plate is being subducted beneath the Pacific Plate. The study area lies within the collision-dominated central South Island.

1.4.1 The Central South Island

The central South Island is a region of oblique convergence between continental crust of the Pacific Plate and continental crust of the Australian Plate. There is both parallel and perpendicular motion occurring at the boundary, which is, in this region, represented by the Alpine Fault (Walcott, 1998). In the last 6.4 million years, approximately 90 km of compression (perpendicular movement) has occurred in the central South Island region, giving rise to the formation and erosion of the Southern Alps, which continue to rise at approximately 11 mm per year (Walcott, 1998). Uplift is, however, almost equalled by rates of erosion (Aitken, 1999). This oblique convergence is also responsible for the numerous faults within Canterbury.

Along with compression, geoscientists estimate that over the last 10 million years there has been a total of 470 km of dextral, strike-slip or parallel motion, meaning that the rocks of eastern Nelson on the Australian Plate were once adjacent to those of western Otago on the Pacific Plate (Aitken, 1999). In total, the Pacific Plate is moving at an average rate of 37 mm per year relative to the Australian Plate (Aitken, 1999).

1.5 Previous natural hazard assessments of the lake areas

There are no previous natural hazard assessments specific to the Canterbury lakes. However, there have been some regional assessments of individual hazards. For example, a comprehensive earthquake hazard and risk assessment was initiated by Environment Canterbury in 1997. Studies undertaken in response to this include Pettinga *et al.* (1998), Stirling *et al.* (1999), Kingsbury *et al.* (2001), Pettinga *et al.* (2001), Stirling *et al.* (2001), Stirling *et al.* (2002), Yetton and McCahon (2006), and Stirling *et al.* (2007).

1.6 Research Approach and Thesis Structure

The primary reason for undertaking a natural hazard assessment is to reduce as much as possible, a community's vulnerability to the consequences of a natural hazard event. This can be achieved by compiling adequate and accurate information concerning a region's hazards, thus enabling satisfactory decisions to be made by all stakeholders involved. An understanding of both the physical and social environments of the lake areas is required. In order to understand the present day physical processes occurring with the lake regions, it is necessary to understand what has occurred within their geological histories. This is achieved by reviewing previous geological studies, maps and records.

A study of the social environments is also important in order to identify how fast an area is expected to grow and also to identify areas most likely to experience development in the future. This is achieved by reviewing population and tourism trends, and land ownership of the lakeside areas. The areas around the lakes with the most potential for future development are of interest as a hazard assessment of these areas is a first priority.

Once the physical and social environments have been established they can be combined to establish the vulnerability of each area to natural hazards. The natural hazards considered in this study are earthquakes, landslides and climate hazards. This study comprises seven chapters:

- **Chapter One** introduces the aims and demonstrates the significance of the study. It also provides background information, which introduces the tectonic setting of New Zealand and explains why the country is vulnerable to earthquakes, landslides and climate hazards in the first place.

- **Chapter Two** provides a summary of the past and present day geological and geomorphological processes of the lake areas.

- **Chapter Three** introduces the social environment of the lake areas. It outlines the current development and population at Lakes Lyndon, Coleridge and Tekapo, summarises population and tourism trends for Canterbury, and identifies specific areas around each of the lakes with potential for development.

- **Chapter Four** is an investigation into earthquake hazards. It identifies seismic sources relevant to the lake areas and discusses the likely consequences of earthquakes in these areas.

- **Chapter Five** examines landslide hazards of the lake areas. It summarises past significant landslide events around the Lakes Lyndon, Coleridge and Tekapo, and identifies areas around the lakes, which may be susceptible to future slope instabilities and their consequences.

- **Chapter Six** is an investigation of current climate hazards of the lake areas. It also looks into the likely effects of climate change.

- **Chapter Seven** is a discussion and conclusions chapter, which brings all of the hazards together and discusses their effects on areas of future potential development.

CHAPTER 2 –

THE GEOLOGY AND GEOMORPHOLOGY OF LAKES LYNDON, COLERIDGE AND TEKAPO

2.1 Introduction

Lakes Lyndon, Coleridge and Tekapo are situated within a dynamic landscape, which has been shaped over millions of years. In order to understand the present day processes occurring within the regions, it is necessary to understand what has occurred within their geological history. Therefore, an account of the past and present day geology and geomorphic processes of each of the lake areas is provided. This chapter is divided into three periods, the preglacial period, the glacial period and the postglacial period.

2.2 The Preglacial Geology and Geomorphology of Canterbury

The New Zealand continental crust, of which only ten percent is above sea level today, developed as part of the active margin between the great southern supercontinent Gondwanaland and its neighbouring super-ocean (Thornton, 2003). The rocks that formed at or near this margin between 520 Ma (million years ago) and 110 Ma make up the basement rocks of New Zealand (Mortimer, 2004). These basement rocks are typically divided into three broad informal units; the Western Province, the Median Zone and the Eastern Province (Figure 2.1) (Coates, 2002). The Canterbury Region lies within the Eastern Province, which is made up of Permian to Cretaceous sedimentary and volcanic rocks (ibid). A Cretaceous-Tertiary cover sequence covers most of the basement rocks in the region, which is in turn overlain by younger Quaternary deposits. For reference purposes a geological time scale is presented in Table 2.1.

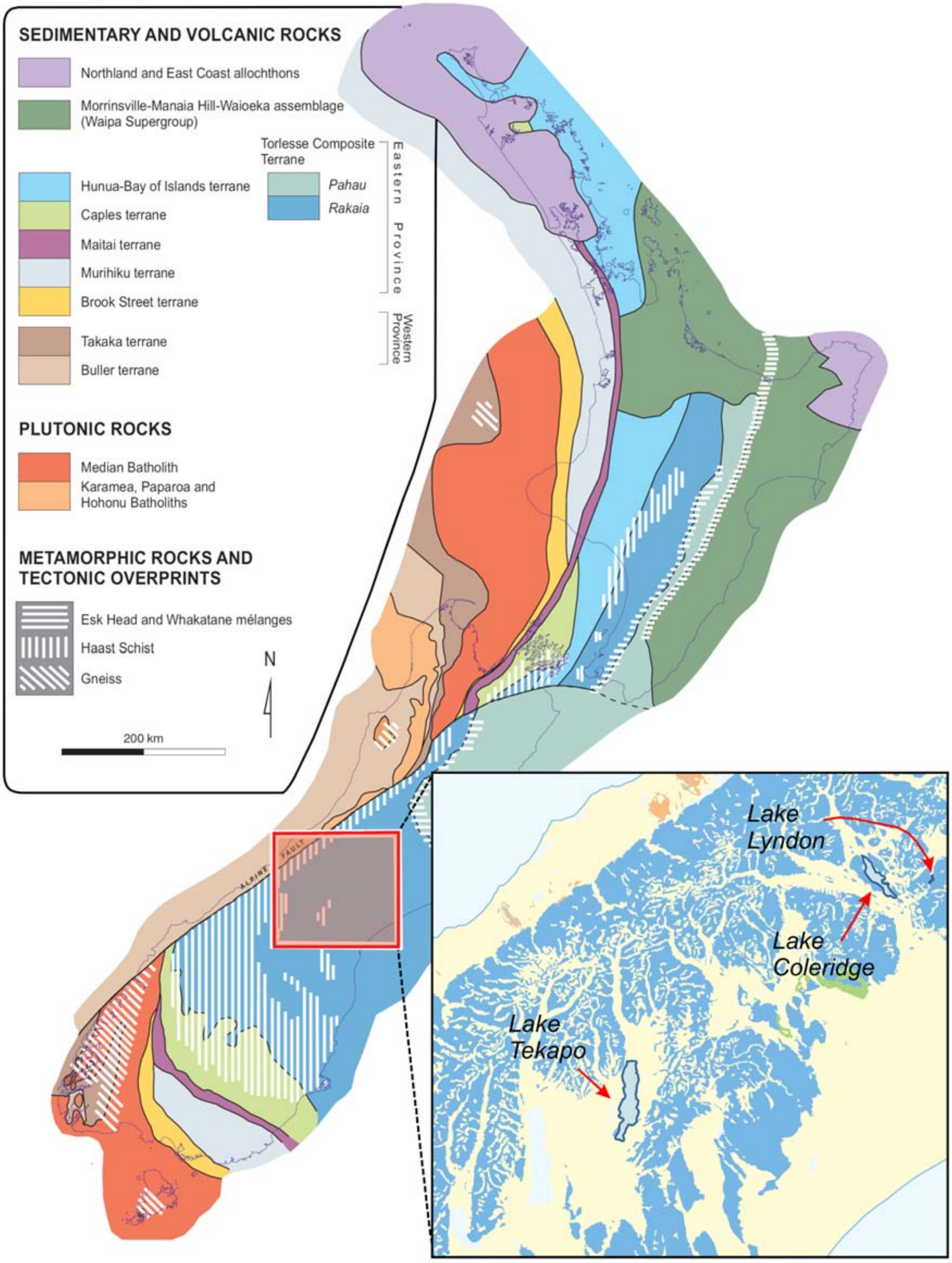

Figure 2.1: The basement rocks of New Zealand, subdivided into tectonostratigraphic terranes. The insert map shows more detail for the lake areas, with pale yellow representing Late Cretaceous to Cenozoic sedimentary and volcanic cover rocks. The Torlesse terrane is differentiated into the Rakaia terrane (blue) and the Jurassic Clent Hills Group (light green), the latter being younger and equivalent in age to Pahau terrane rocks of the north-eastern South Island. Modified from Cox & Barrell, (2007): 4.

Table 2.1: Geological time scale. Modified from Thornton, (2003).

ERA	PERIOD	EPOCH	MILLIONS OF YEARS AGO
Cenozoic	Quaternary	Holocene	0.01
		Pleistocene	1.81
	Tertiary	Pliocene	5.3
		Miocene	23.8
		Oligocene	33.7
		Eocene	54.8
		Paleocene	65
Mesozoic	Cretaceous		142
	Jurassic		206
	Triassic		248
Paleozoic	Permian		290
	Carboniferous		354
	Devonian		417
	Silurian		443
	Ordovician		490
	Cambrian		540
Precambrian			

2.2.1 Canterbury Basement Rocks and their Depositional History

The basement rocks of Canterbury consist mainly of the Torlesse Supergroup, an extensive sedimentary deposit, which is subdivided into two terranes. The Rakaia Terrane (older Torlesse) makes up southern and central Canterbury, and is Permian to Late Triassic in age. North Canterbury overprints the Pahau Terrane (younger Torlesse), which is Middle Jurassic to Early Cretaceous in age (Field & Browne, 1989). The boundary between these two terranes is marked by the Esk Head Mélange, a narrow belt comprised of sediment from both terranes along with conglomerate, chert and limestone (Figure 2.1) (Thornton, 2003).

2.2.1.1 The Rakaia Terrane

Lakes Lyndon, Coleridge and Tekapo lie within the Rakaia Terrane, which consists primarily of a quartzofeldspathic sandstone to mudstone association (Mortimer, 2004).

Sediment from this association was sourced from a continental volcanoplutonic arc and subsequently deposited in a turbiditic submarine environment (ibid). Small amounts of conglomerates, volcanic units, crystalline limestone and chert also occur within the terrane (Field & Browne, 1989). Deformation of this terrane is evident from its multiple folds and steeply dipping bedding (Mortimer, 2004). The south-west region of the Rakaia Terrane grades laterally into its metamorphosed contingent, the Haast Schist, which outcrops in small amounts to the east of Lake Tekapo. Geological maps of Lakes Lyndon, Coleridge and Tekapo are presented in Figures 2.2 and 2.3.

2.2.2 Canterbury Cover Sequences and their Depositional History

A mountain building episode, known as the Rangitata Orogeny, occurred during the Early Cretaceous, thrusting, tilting and folding the Torlesse bedrock and exposing it to subaerial erosion (Fox, 1987). Eventually erosion processes exceeded those of uplift and as the mountains wore down, a nearly level peneplain was formed (Bradshaw, 1985). Thinning of the continental crust also occurred as New Zealand separated from Gondwana around 85 Ma. This led to subsidence and to a new set of deposits, referred to as cover sequences, forming on top of the Torlesse (Coates, 2002).

2.2.2.1 Cover Sequences in the Lyndon and Coleridge Region

Lakes Lyndon and Coleridge lie within the glaciated valleys of the Rakaia River Catchment, which only contain a very sparse amount of Cretaceous and Tertiary cover rocks (Lee, 2004; Wood *et al.*, 1989). Events such as uplift during the Kaikoura Orogeny and glacial processes during the Quaternary led to extensive erosion of pre-existing Cretaceous and Tertiary rocks. These rocks now occur only in fault angle depressions (Wood *et al.*, 1989). The nearest Cretaceous-Tertiary rocks to the lakes occur at Redcliffe on the southern side of the Rakaia River, in the Acheron Valley to the south-west of the lakes, and to the north-east of the lakes, in the Castle Hill Basin (Lee, 2004; Soons, 1963; Wood *et al.*, 1989).

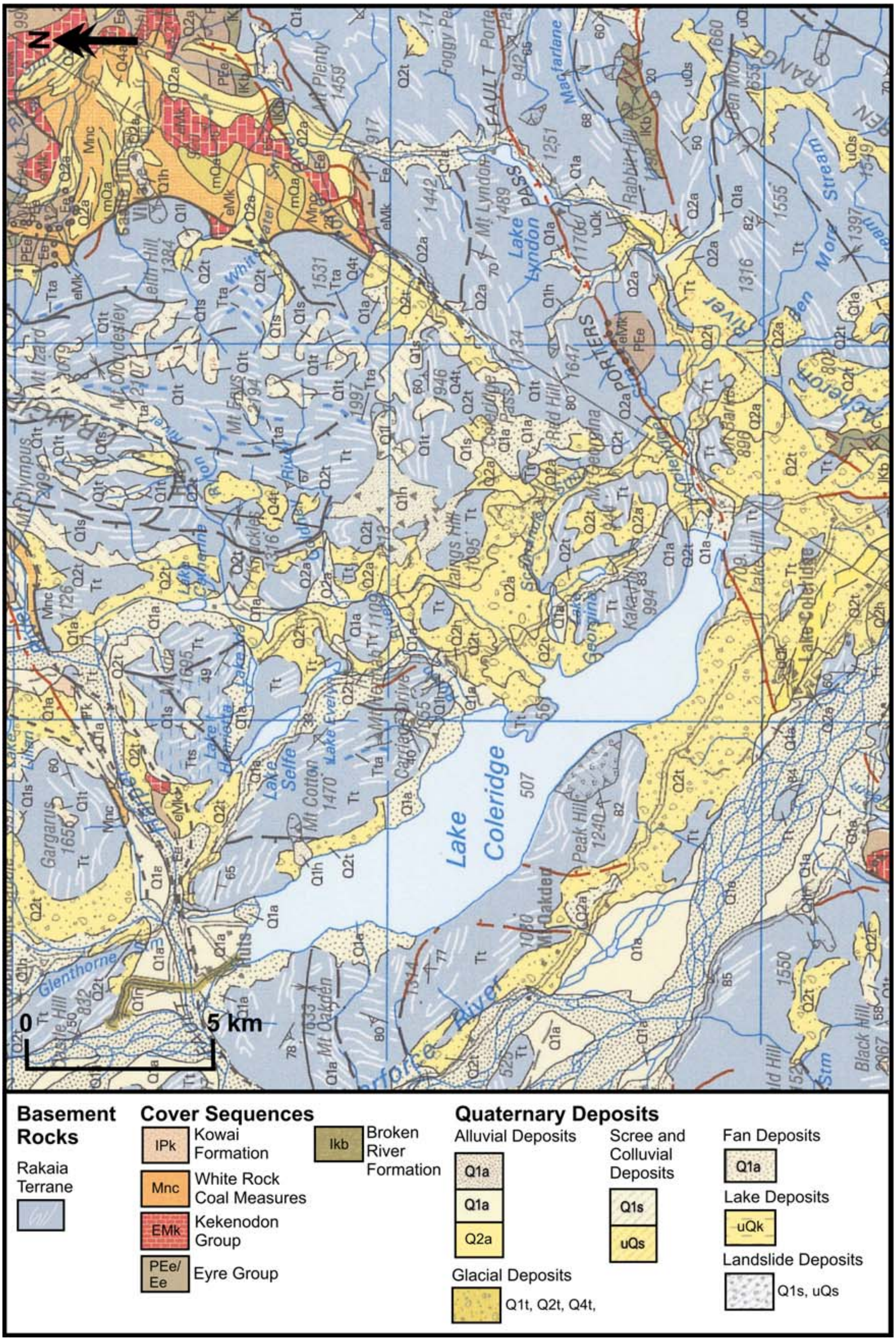

Figure 2.2: The geology of the Lakes Lyndon and Coleridge region. Modified from Cox & Barrell,(2007).

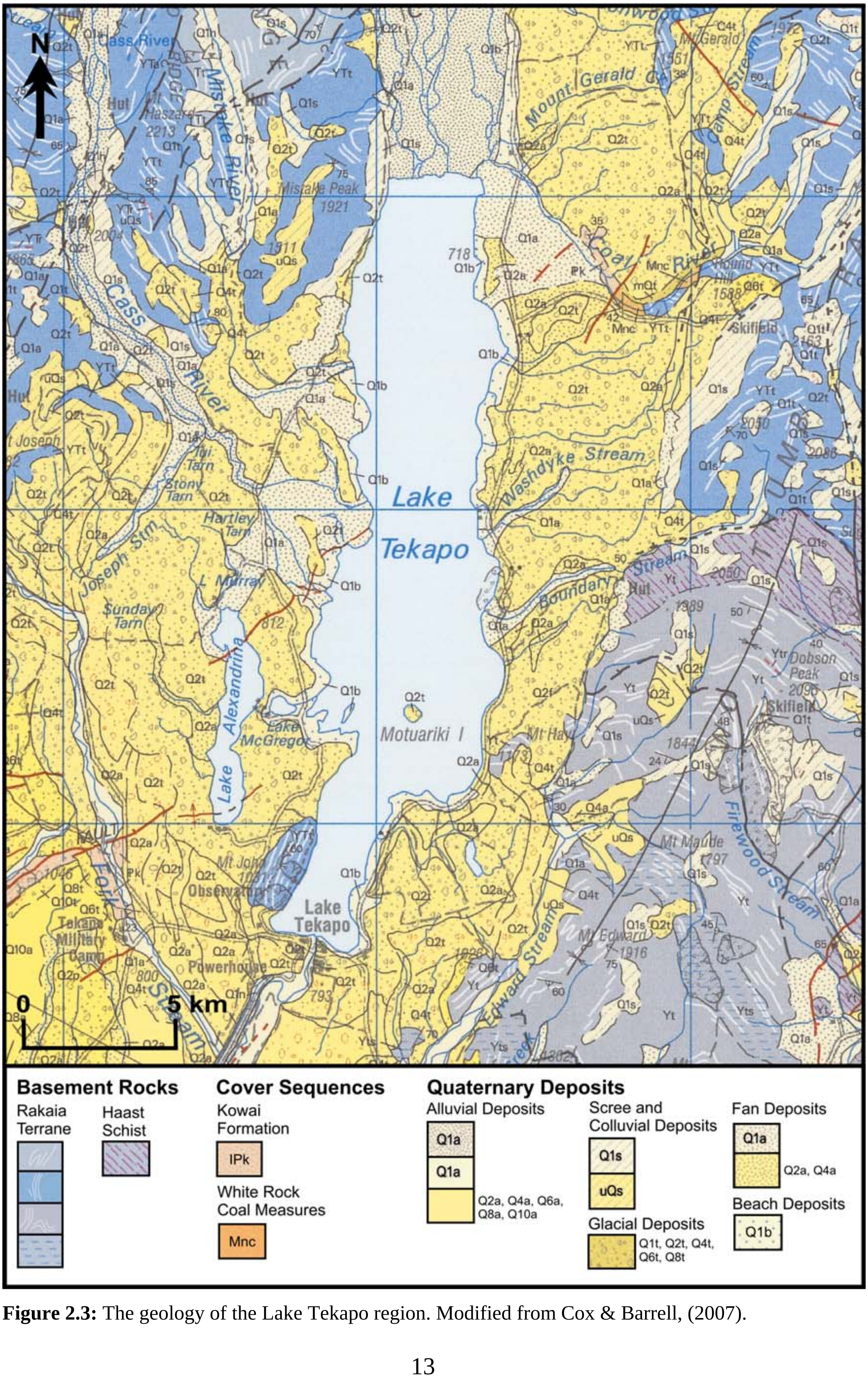

Figure 2.3: The geology of the Lake Tekapo region. Modified from Cox & Barrell, (2007).

2.2.2.2 Cover Sequences in the Tekapo Region

Lake Tekapo lies within the intermontane Mackenzie Basin, which first formed during the commencement of the Kaikoura Orogeny in the Late Oligocene/Early Miocene (Fox, 1987). It was during this time that the present plate boundary between the Australian and Pacific plates was activated and the present day Southern Alps were formed (Field & Browne, 1989; Thornton, 2003). During the marine transgression prior to this Orogeny, marine greensands and coal measures were deposited in the southern and eastern area of what is now the present basin (Fox, 1987). Remnants of these deposits are found to the east of Lake Tekapo in Coal River and north of Lake Tekapo at Lilybank Station (ibid). However, with the onset of the Kaikoura Orogeny, the marine transgression period was followed by regression, as once again, substantial uplift of the Torlesse basement occurred (Field & Browne, 1989). As a consequence of this process, most of the existing Tertiary sediment within the Mackenzie Basin was stripped away (ibid).

Today, the Torlesse Basement within the Mackenzie Basin has been partly buried by gravel and finer sediments of the Neogene (Miocene to Pliocene), which are in turn overlain by younger Pleistocene sediments (Mildenhall, 2001). The Neogene deposits are known as the White Rock Coal Measures and the Kowai Formation. According to Gair (1978), the White Rock Coal Measures consist of quartz sand, clay, shale and lignite seams. The overlying Kowai Formation, locally referred to as the Glentanner beds, consists of sandstone, conglomerate and mudstone (Field & Browne, 1986). Stratigraphic successions have been studied just north east of Lake Tekapo at Stony Stream and Coal River (ibid). However, these successions are not completely certain due to localised slumping (ibid). Units of clay, sandstone, hard coal and lignite have been observed at these localities, which most likely belong to the White Coal Rock Measures. These units underlie a thick conglomerate unit (approximately 35 m) belonging to the Glentanner beds (ibid). The White Rock Coal Measures were deposited in a non-marine to marginal marine environmental setting, and are indicative of continued regression (Field & Browne, 1989).

As uplift of the surrounding ranges continued to develop, terrestrial fluvial sedimentation occurred resulting in major gravel fan deposits (Mildenhall, 2001; Upton *et al.*, 2004). Lacustrine deposits of clay, silt and sand also accumulated within ponded areas and these deposits are also part of the Kowai Formation (Field & Browne, 1986).

2.3 The Geology and Geomorphology of Canterbury during the Quaternary Glacial Period

As uplift during the Kaikoura Orogeny accelerated c. 5 Ma, the north-east to south-west trending Southern Alps developed into an extensive topographic high, which started to interfere profusely with the prevailing westerly winds (Rother & Shulmeister, 2006). This interaction led to intense orographic precipitation, with a wetter climate prevailing on the windward side of the Southern Alps (Sturman *et al.*, 1999). Due to high levels of precipitation just west of the main divide, a narrow superhumid zone (about 30 km wide) formed, stretching the full length of the Southern Alps (Fitzsimons, 1997; Rother & Shulmeister, 2006). As the climate cooled during the Pliocene and Pleistocene, sea levels consequently dropped, increasing the relative height of the Southern Alps. This had the effect of intensifying the orographic effects, which produced very high levels of snowfall within the superhumid zone (Rother & Shulmeister, 2006). As a result, ice began to accumulate, producing extensive ice fields or a possible narrow ice cap, with valley glaciers propagating outwards (ibid). These glaciers were very extensive, reaching the Tasman Sea in the west and spreading out beyond the foothills to the outwash plains in the east (Gellatly *et al.*, 1988).

Even though glaciation within New Zealand is believed to have commenced c. 2.6 to 2.4 Ma, the glacial record for the older events is poorly constrained and a stratigraphic glacial record only exists for the last c. 300,000 to 350,000 years ago (Newnham, 1999; Suggate, 1990). During this time, several glacial advances took place within the major valleys of the Southern Alps (Wood *et al.*, 1989). The last four major glaciations are referred to as the Nemona, Waimaunga, Waimea and Otira Glaciations (Suggate, 1990) (Table 2.2). However, specific nomenclature has been adopted for the glacial episodes within each major catchment. As each valley glacier advanced and receded, a succession of deposits was laid down (Wood *et al.*, 1989). Approximate limits of these ice advances are shown in Figure 2.4.

Table 2.2: New Zealand glacial and interglacial periods over the last c. 370,000 years. Modified from: www.teara.govt.nz

GLACIAL PERIOD	INTERGLACIAL PERIOD	YEARS BEFORE PRESENT
	Aranui	0 – 14,000
Otira		***14,000 – 80,000***
	Kaihinu	80,000 – 120,000
Waimea		***120,000 – 190,000***
	Karoro	190,000 – 220,000
Waimaunga		***220,000 – 280,000***
	-	280,000 – 320,000
Nemona		***320,000 – 370,000***

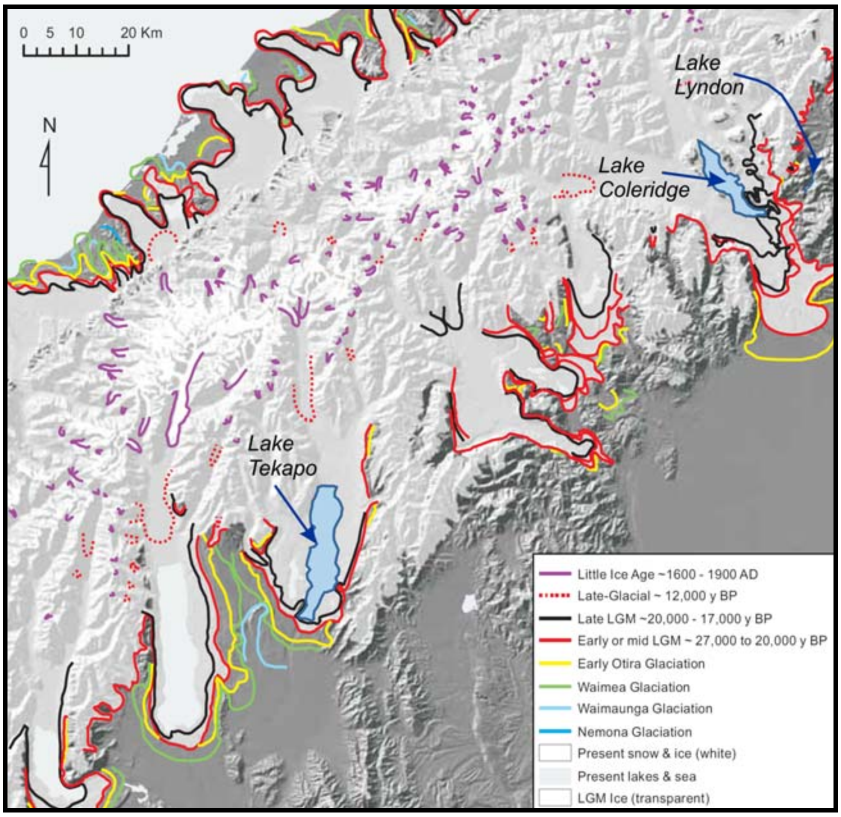

Figure 2.4: Approximate limits of mid-to-late Quaternary ice advances in the central South Island. Modified from Cox & Barrell,(2007): 34.

There are well-preserved Late Pleistocene glacial sequences throughout Canterbury, including the Rakaia Valley, in which Lakes Lyndon and Coleridge lie, and in the Mackenzie Basin, where Lake Tekapo is located. Remnants of glacial sequences within these two areas include moraines, fluvioglacial sediments and lacustrine (lake) sediments (Wood *et al.*, 1989).

2.3.1 Glacial History of the Lake Lyndon and Coleridge Region

The glacial history of the Lake Coleridge area has been taken from the well-preserved glacial succession of the Rakaia Valley. Multiple glacial advances are thought to have occurred within the Rakaia Valley during the Pleistocene and Holocene with the latest minor advance occurring as little as c. 100 years ago (Burrows & Maunder, 1975). Four major ice advances have been identified within the valley and are all regarded as Late Pleistocene in age (Soons, 1963). The oldest event, which corresponds with the early Otira Glaciation, is referred to as the Woodlands Advance (Cox & Barrell, 2007). This advance was followed by the Tui Creek, Bayfield and Acheron Advances, which all correspond to the mid to late Otira Glaciation (Soons, 1963).

The surficial glacial deposits which occur around Lake Coleridge have been attributed to the last major advance, the Acheron Advance, which occurred approximately 10,000 to 14,000 years ago (Figure 2.5) (Soons, 1963; Wood *et al.*, 1989). This advance consists of three separate but closely spaced advance episodes, named the Acheron-1, Acheron-2 and Acheron-3 Advances. During the Acheron Advance, two distinct ice streams are believed to have been present (Soons, 1963). Besides the well-documented Rakaia Glacier, another major glacier, the Coleridge or Wilberforce Glacier, occupied the trough in which Lake Coleridge lies today (ibid). Lobes of this glacier spread into the valleys east of the lake and as a result of the Acheron Advances there is a complex array of glacial depositional features present today, especially in the area south-west and south-east of Lake Coleridge. Features include terraces, outwash surfaces, moraines and kettle depressions (Howard, 2001). These glacial deposits, referred to as till, are comprised primarily of reworked Torlesse Supergroup rocks (ibid). The till is characterised by a wide range of particle sizes, from large boulders approximately one metre in diameter, to fine silts. A rapid contraction of glaciers is thought to have occurred subsequent to the Acheron Advance, with glaciers becoming confined to the narrow upper reaches of the valleys (Soons, 1994; Suggate, 1990).

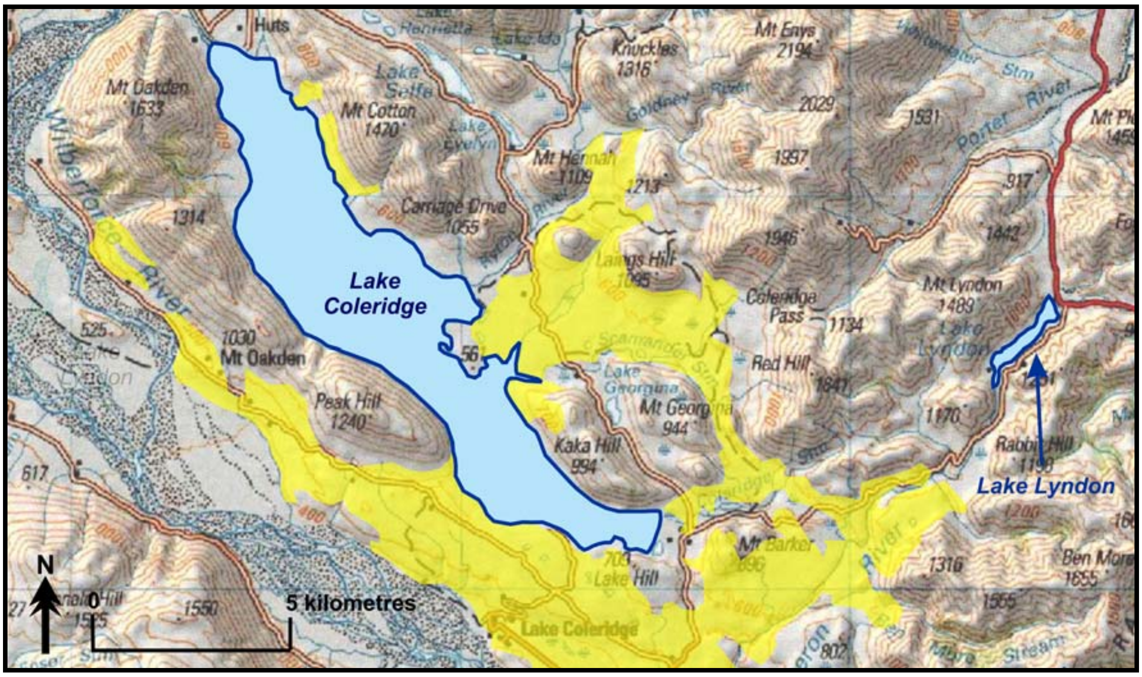

Figure 2.5: Glacial deposits around Lakes Coleridge and Lyndon (indicated in yellow).

2.3.1.1 Lake Lyndon

Lake Lyndon occupies a short valley, which has been referred to as the Lyndon-Acheron Valley by Soons and Burrows (1978). This valley starts just north of Lake Lyndon and terminates where it opens up into the Rakaia Valley. According to Soons (1963) at least one major glacial advance, the Tui Creek Advance, occupied the valley during the Pleistocene. However, mapping by Cox & Barrell (2007) suggests that this area was kept free of ice (Figure 2.4). Either way the area was affected indirectly by glaciation.

The southward flowing drainage of the Lyndon-Acheron Valley was obstructed with each advance of the Rakaia and Coleridge Glaciers (Soons & Burrows, 1978). As a northward sloping outwash surface was created with each advance, ponding of streams occurred and a switch to a northerly outflow towards the Castle Hill Basin developed (ibid). With each glacial recession, drainage within the valley reverted back to its usual southerly outflow (ibid). According to Gage (1959), Lake Lyndon itself developed as a result of damming of the local drainage by alluvial fans. A whole series of alluvial fans currently comprises the floor of the Lyndon-Acheron Valley (Soons & Burrows, 1978).

2.3.2 Glacial History of the Lake Tekapo Region

Like Lake Coleridge, the landscape at Lake Tekapo is primarily a result of glacial processes during the Pleistocene. The Godley Glacier, of which only a small remnant exists today, occupied Lake Tekapo and its surroundings for much of the Pleistocene. The Godley Glacier was one of four major glaciers in the upper Waitaki Region, which produced outwash deposits that later coalesced to form the extensive plains within the Mackenzie basin (Oborn, 1978). As each glacier fluctuated in response to a wavering Pleistocene climate, a series of well-preserved deposits were left behind.

The oldest glacial event in the area is referred to as the Wolds advance, with remnants of its moraine and outwash being preserved to the south-west of Lake Tekapo (Figure 2.6). The age of this advance is disputed and has been attributed to being Waimean or Waimaungan in age (Fox, 1987; Suggate, 1990). The Wolds advance was then followed by the Balmoral advance, which has formed well-preserved deposits right around the Lake Tekapo region. Again, a firm age for this event is not known, but it most probably occurred during Early Otiran times (Suggate, 1990). The most extensive glacial deposits surrounding Lake Tekapo are attributed to the Mount John and Tekapo advances, which correlate with the Otira Glaciation. Age estimates for the Mount John advance range from about 18,000 to 16,000 years ago, while an age for the Tekapo advance is estimated at between 15,000 to 14,000 years ago (Fitzsimons, 1997). The moraines formed by the Tekapo advance effectively dammed the valley, which led to the formation of Lake Tekapo (Oborn, 1978). The Tekapo Formation consists of the Tekapo moraine and its associated outwash (Mager & Fitzsimons, 2007).

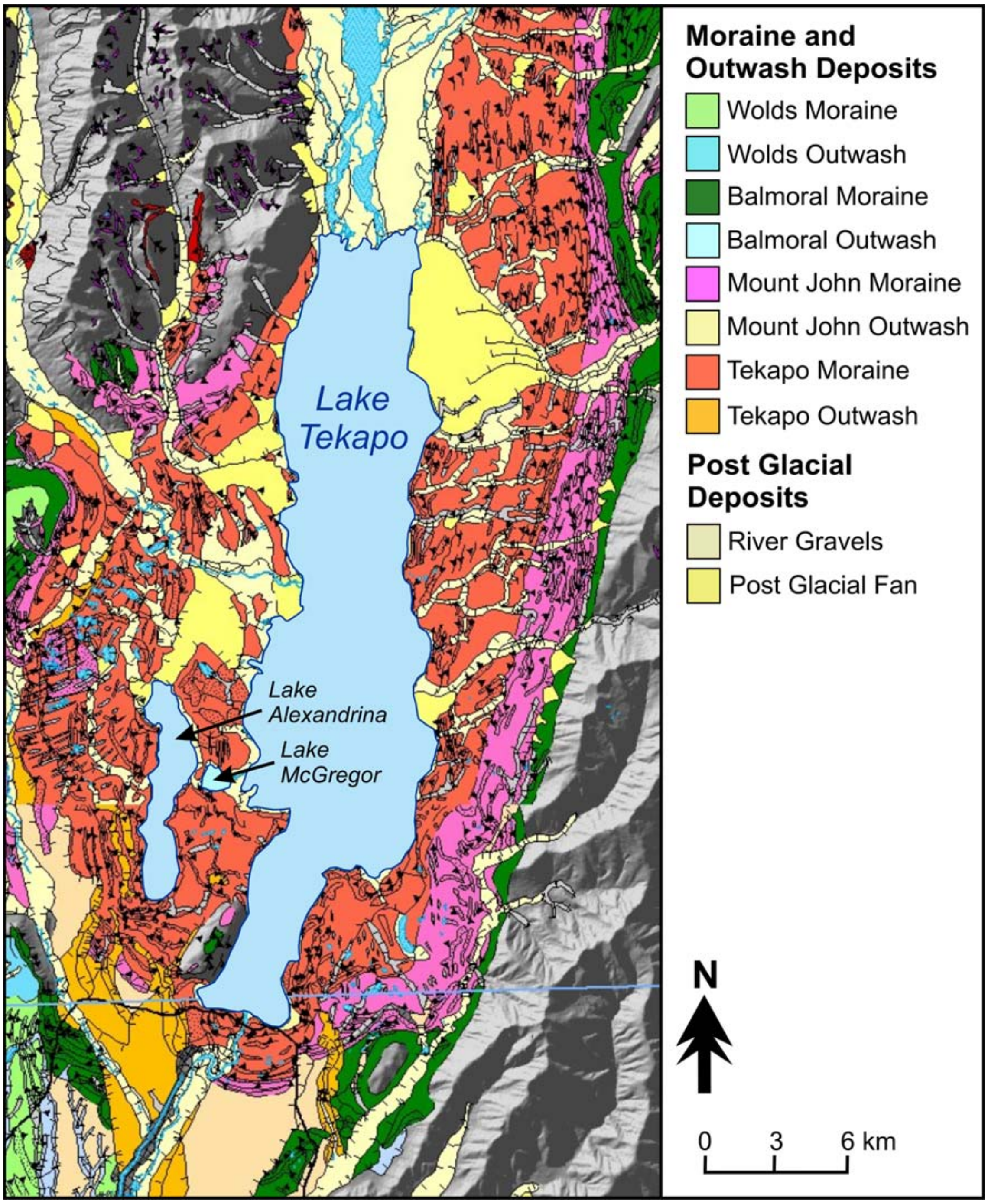

Figure 2.6: Glacial deposits around Lake Coleridge. Modified from the Central South Island Glacial Geomorphology online map from www.gns.cri.nz/.

The glacial moraines are composed of till: sub-rounded to well-rounded Torlesse greywacke (predominant component), low-rank schist and argillite along with their fine-grained derivatives (Oborn, 1978). Particle sizes range from clay size to boulders greater than 10 m in dimension (ibid). The associated outwash gravel is also predominantly Torlesse greywacke, which is well-rounded and moderately well-sorted (ibid). Other than a series of moraines and outwash, other glacial features preserved in the area include kettle lakes, drumlins and roches moutonnées. Mount John, Moutuariki Island, Mount Hay and Wee McGregor form a chain of roches moutonnées, remnants of bedrock that were shaped by ice during the Pleistocene (Fox, 1987). They may have once formed a continuous bedrock scarp (ibid).

2.4 The Post Glacial Geology and Geomorphology of Canterbury

About 14,000 years ago, global temperatures started to increase, causing worldwide glacial recession (Erickson, 1996; Roberts, 1998). By this time in New Zealand, the glaciers from the last glacial maximum had significantly receded, but ice still partly occupied the major valleys of the Southern Alps (Soons, 1994). Although this deglaciation process was unsteady, with minor readvances occurring into the Holocene, a period of major environmental change had begun, from an almost glacial environment to that of the present day (ibid). A rapid contraction of New Zealand glaciers is thought to have occurred between twelve and nine thousand years ago (Gellatly *et al.*, 1988).

As a result of this predominantly warming climate, the landscape started to make adjustments, as the glacial recession had caused significant instability within the landscape. Although duration of adjustment varies between locations, depending on how far an area is from reaching a point of stability or equilibrium, the most intense period of readjustment would have lasted three to four thousand years (Soons, 1994).

The recession of glaciers was responsible for altering the geomorphology in both a direct and indirect way (Roberts, 1998). Landforms, such as moraines and kettle lakes were created directly by glacier retreat (refer to sections 2.3.1 and 2.3.2). Other landforms were created indirectly by deglaciation, primarily as a result of glacial meltwater processes (ibid). Mass movement and aeolian processes also played a role in shaping the current geomorphology of Canterbury.

2.4.1 Adjustment of Fluvial Systems

As glaciers rapidly receded towards the end of the last major glaciation, meltwater drained from the glaciers in the form of large braided rivers. Vast quantities of debris were transported by these rivers, forming extensive outwash plains, such as the Canterbury Plains. Changes in existing stream channels also accompanied ice retreat. Numerous ice drainage systems were abandoned and streams often altered their courses (Soons, 1994).

2.4.1.1 Adjustment of Fluvial Systems around Lakes Lyndon and Coleridge

Significant changes occurred to the major rivers and streams around Lake Coleridge following deglaciation. According to Speight (1934; Speight *et al.*, 1910), in pre-glacial times the Wilberforce River, a major tributary to the Rakaia River, flowed down the valley now occupied by Lake Coleridge (Figure 2.7). The river would most probably have entered the Rakaia through a gap just east of Peak Hill, which is now blocked by moraine. After glacial recession, the Wilberforce River forsook its old route and instead of flowing between Mount Oakden and Mount Cotton into Coleridge valley, it changed to its present day position, flowing between Mount Oakden and Mount Algidus and into the Rakaia River. The Harper River is thought to have once flowed east of Lake Coleridge in a valley running parallel to the lake, before altering its direction significantly to its present day course (Figure 2.7) (Speight *et al.*, 1910). Relict alluvial fan deposits to the south of Round Hill and Laings Hill suggest that the Ryton River probably once flowed between these two hills before changing its course to its present day location. As ice withdrew from the region, the river altered its course so that it flowed between Round Hill and Mount Hennah and out into the lake, eventually incising into its riverbed, cutting off the previous outlet to the aggrading fan (Lee, 2004).

As previously mentioned in section 2.3.1.1, streams which had a normally southern trending flow were obstructed by ice and outwash deposits during glacial periods, resulting in a consequent switch to a northerly flow (Soons & Burrows, 1978).

Following deglaciation, these streams once again reverted to their southerly flow direction, becoming inflow sources for the newly formed lake. Multiple small lakes and swampy areas within the Lake Coleridge area are a direct result of drainage obstruction. Lake Coleridge began to drain at its northern end as it does today, through Lake Stream, a small stream, which flows from the northern tip of Lake Coleridge into the Harper River.

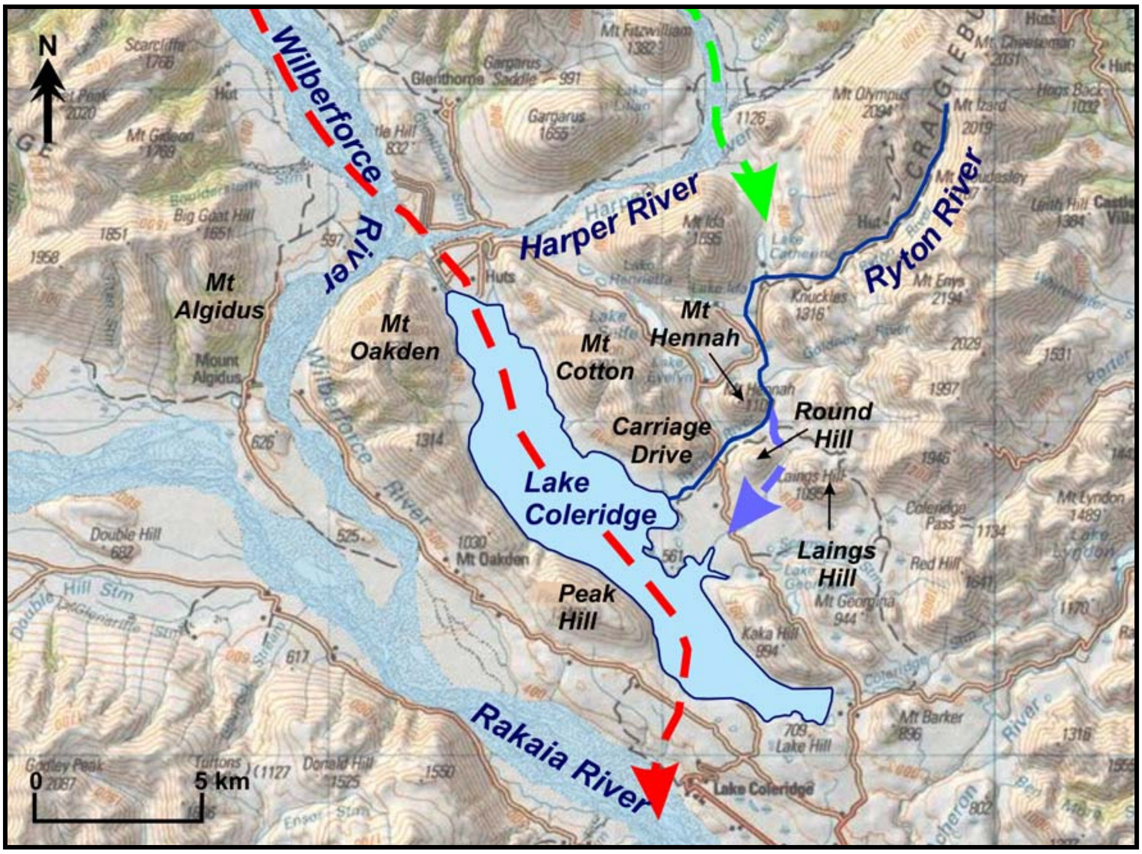

Figure 2.7: Present day and pre-glacial courses of the major rivers around Lake Coleridge. The Wilberforce River is thought to have once followed the route indicated by the red arrow and the Harper River is once thought to have flowed east of Lake Coleridge in a valley indicated by the green arrow. The Ryton River is thought to have flowed down the path indicated by the blue arrow before deglaciation.

2.4.1.2 *Adjustment of Fluvial Systems around Lake Tekapo*

Numerous river channels dissect the landscape around Lake Tekapo, draining from the neighbouring ranges into the Godley River or into the lake. Many of these channels, particularly in the north-eastern area, have since been abandoned, while others have incised deeply into the surrounding deposits. These two features suggest that meltwater or sediment may have decreased remarkably during the Holocene. Multiple abandoned channels running south of the lake also suggest the presence of a meltwater fluvial system which was much larger than today. However, there is no evidence to suggest that all these channels were active simultaneously. They may be the result of a river frequently altering its course.

2.4.2 Adjustment of Rock Slopes

Glacial recession from a valley exposes a typically unstable landscape that is consequently susceptible to rapid change (Ballantyne, 2002). The steep sides of the previously glaciated valleys tend to become very unstable due to debuttressing; the removal of lateral support once provided by the ice (Ballantyne, 2002; Gage, 1959). This leads to a change in the state of stress existing within the rock mass and to subsequent slope modification (ibid). According to Ballantyne (2002), the slopes generally respond in one out of three ways, depending on the rock mass properties. However, more than one mode may occur. Slopes may fail as large-scale catastrophic events, such as major rock avalanches and rock falls, or by frequent discrete rock fall events. Slow, large-scale rock mass deformation may also occur, which can subsequently lead to a large-scale catastrophic event.

These three rock slope adjustment events become less frequent with time as the slopes approach a state of equilibrium (Ballantyne, 2002). However, the time it takes for a slope to relax and reach an equilibrium state can be prolonged, with an order of 10^2 to 10^3 years for rock mass deformation, 10^3 to 10^4 years for small to medium rock fall events and $>10^4$ years for large-scale catastrophic events (ibid). In tectonically active regions, such as Canterbury, seismicity may trigger the failure of slopes with reduced rock mass stability (Ballantyne, 2002).

2.4.2.1 Adjustment of Rock Slopes around Lakes Lyndon and Coleridge

At least two modes of rock slope adjustment seem to have occurred in the region of Lake Lyndon and Coleridge. A number of large-scale catastrophic events have occurred in the vicinity, including the Craigieburn, Acheron and Lake Coleridge Rock Avalanches. These events were seismically triggered and are described further in Chapter 5. Antiscarps are also prevalent in the area, suggesting a large amount of slow, large-scale rock mass deformation. Landslide hazards to the lake areas are also described in Chapter 5.

2.4.2.2 Adjustment of Rock Slopes around Lake Tekapo

From air photo interpretation, it appears that rock slope adjustment in the immediate vicinity of Lake Tekapo has been in the form of frequent discrete rock fall events. Small talus deposits line the base of the Two Thumb Range to the east of Lake Tekapo and along the base of the Hall Range to the north-west of the lake. The greywacke/argillite within the Mount Cook region is highly jointed and relatively unstable (Augustinus, 1992; Augustinus, 1995b). Although this rock exhibits a high resistance to abrasion, the closely spaced joints means that it has a low rock mass strength (Augustinus, 1992). Consequently, rock slope failure would have been most prominent during and shortly after glacial recession, resulting in the formation of relatively low angle slopes in strength equilibrium (Augustinus, 1992; Augustinus, 1995a). Consequent zones of weakened rock would most probably have been exploited by glacial readvances, resulting in a wide, flat glacial trough (Augustinus, 1995b). Ridge rents or antiscarps observed in the Mount Cook Region, indicate that large-scale rock mass deformation has also occurred (Augustinus, 1995a). Large-scale catastrophic events have also occurred in the vicinity and these are described in Chapter 5.

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2.5 The Present-Day Geomorphology of Lakes Lyndon, Coleridge and Tekapo

2.5.1 The Present-Day Geomorphology of the Lake Lyndon Region

Lake Lyndon is a relatively small, elongated lake nestled in the foothills of the Southern Alps near Porters Pass, Canterbury. The lake, which trends north-east to south-west, has a maximum length of c. 3.5 km and a maximum width of c. 550 m. The lake is also relatively shallow with a maximum depth of 18.3 m (Irwin, 1985). Due to its shallow nature, the most northern extent of the lake usually dries up over summer (Figure 2.8).

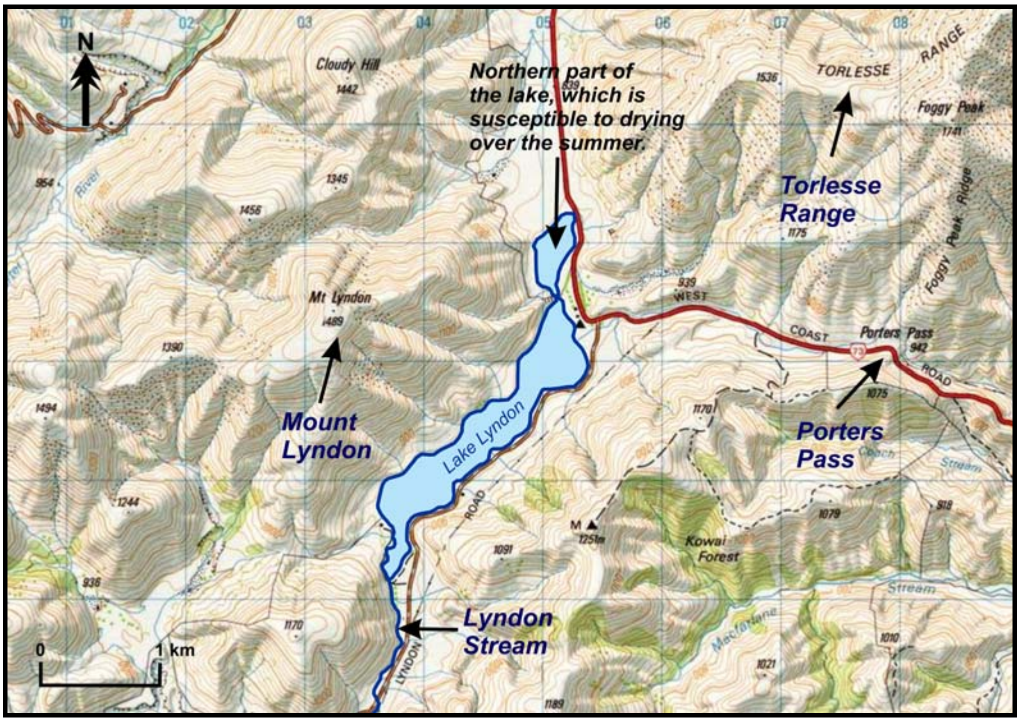

Figure 2.8: Lake Lyndon and its surrounding topography.

The lake is enclosed by alluvial fans sourced from the surrounding steep mountains (Gage, 1959). The highest peak on the western side of the lake is Mount Lyndon, which rises to 1489 m (Land Information New Zealand, 1998). The peak bounding the southern edge of the lake rises steeply to 1170 m and the highest peaks along the eastern side of the lake rise to a maximum of 1251 m (ibid). The southern extent of the Torlesse Range bounds the northern edge of Lake Lyndon, with abutting peaks rising to 1536 m (ibid). The lake drains at its southern end via Lyndon Stream. There are a number of small drainage channels, which drain from the surrounding mountains into the lake.

2.5.2 The Present-Day Geomorphology of the Lake Coleridge Region

Lake Coleridge occupies a north-north-west to south-south-east trending, glacially carved trough situated within the foothills of the Southern Alps, in central Canterbury.

The long and narrow lake, which lies approximately 507 m above sea level, is 17.8 km long with a maximum width of 3.4 km (Figure 2.9) (Biggs & Davies-Colley, 1990).

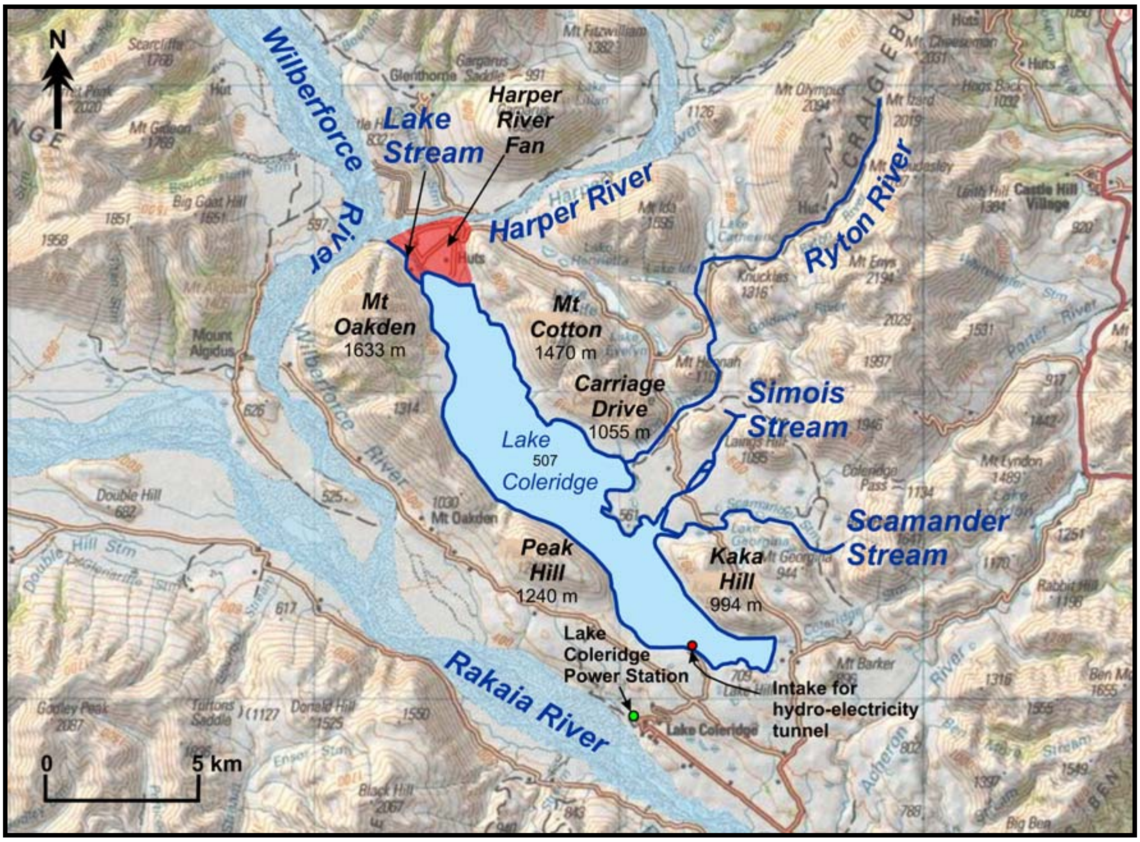

Figure 2.9: Lake Coleridge and its surrounding topography.

The lake lies between two narrow mountain ridges composed of Torlesse Supergroup basement rocks. The highest peaks along the eastern ridge include Mount Cotton (1470 m), Carriage Drive (1055 m) and Kaka Hill (994 m) (Land Information New Zealand, 1998; Land Information New Zealand, 2000). The highest peaks along the western ridge include Mount Oakden (1633 m) and Peak Hill (1240 m) (ibid). The ridge slopes leading down to the lake's edge are very steep (typically c. 45°). A gap exists between the two ridges at the lake's most northern point. The lake is impounded here by an alluvial fan of the Harper River. A gap, roughly 3 km wide, exists half way along the eastern ridge, where a peninsula juts out into the lake. This area of more levelled land is overlain with glacial and river deposits. Lateral and terminal moraines from the Rakaia and Coleridge/Wilberforce glacier impound the southern end of the lake. A series of fans lie at the base of Mount Oakden and a few large fans also protrude into Lake Coleridge from the east.

The Rakaia River runs parallel to the ridge flanking the western side of Lake Coleridge, and lies approximately 150 m below the level of the lake. Two major tributaries of the Rakaia River, the Wilberforce and Harper Rivers, flow just north of the lake, with part of their flow being diverted into the lake for hydro-electric purposes. A number of small streams, which drain from the high country on either side of Lake Coleridge, also help maintain the water supply to the lake (Speight, 1934). The most substantial of these is the Ryton River, which flows into the eastern side of the lake. Other notable streams include the Simois and Scamander Streams, which also drain into the eastern side of Lake Coleridge. The lake discharges at its northern end via Lake Stream. The lake water is also drained from an intake tunnel at its southern end into the Coleridge Power Station and out into the Rakaia River (Carter & Lane, 1996). The slopes of the lake itself are also very steep, except for the northern and southern most ends of the lake and along the delta of the Ryton River (Biggs & Davies-Colley, 1990). The maximum depth of the lake is 200 m (Carter & Lane, 1996).

2.5.3 The Present-Day Geomorphology of the Lake Tekapo Region

Lake Tekapo lies within a north-south trending glacially carved trough, just east of the Southern Alps. The lake is approximately 27 km long and has an average width of 3.5 km in the main body of the lake and 2 km at its southern end (Irwin, 1978). The lake is impounded at its southern end by moraines deposited during the last glacial maximum and lies approximately 707 m above sea level (Figure 2.10) (Graham *et al.*, 2005).

The main inflow to Lake Tekapo is the Godley River, a large braided river, which drains from the Godley and associated smaller glaciers, approximately 35 km north of the lake (Irwin, 1978). The Macauley River, which drains from the Sibbald and Two Thumb ranges, joins the Godley River just before flowing into the northern end of Lake Tekapo (Graham *et al.*, 2005). The Mistake and Cass Rivers drain into the western side of Lake Tekapo from the Hall, Gammack and Liebig Ranges, and Boundary Stream, Coal River and many smaller streams drain into Tekapo's eastern side from the bordering Two Thumb Range. The Tekapo River drains Lake Tekapo from its southern end. There is further outflow for hydro-electric power generation (Irwin, 1978).

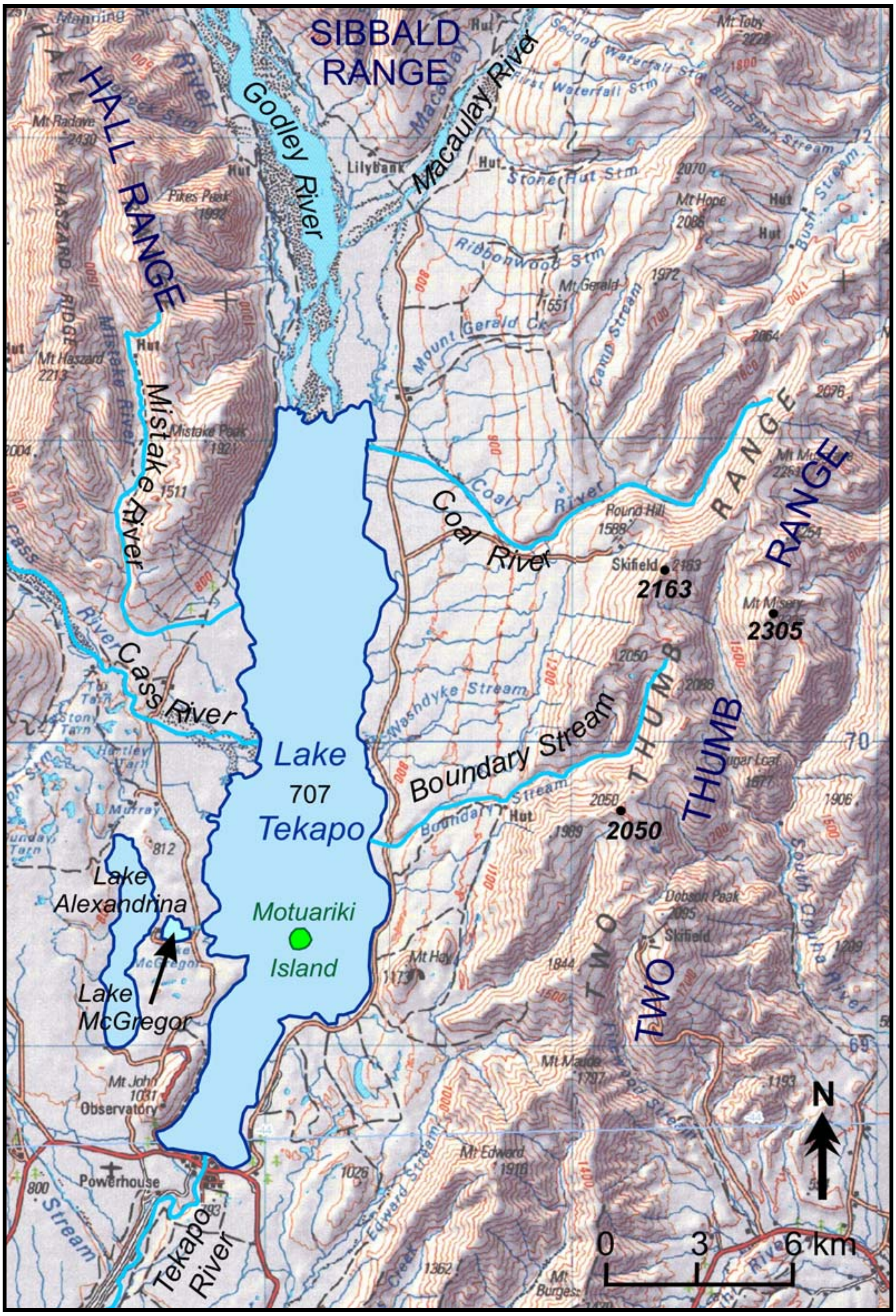

Figure 2.10: Topography surrounding Lake Tekapo.

The topography surrounding Lake Tekapo ranges from relatively flat outwash surfaces and hummocky moraine deposits to steep mountainous terrain (McGowan & Sturman, 1997). The land to the east of Lake Tekapo is characterised by a long and narrow strip of hummocky moraine deposits dissected by multiple streams flowing from the adjacent Two Thumb Range. This narrow strip widens to the north and has an average width of approximately 5 km. The southern end of the adjacent, north-south trending Two Thumb Range rises steeply with peaks exceeding 2000 m (Upton *et al.*, 2004). The area immediately north of Lake Tekapo is dominated by multiple interconnecting channels and an associated floodplain of the large, braided Godley and Macauley rivers. Steep-sided terrain of the Hall Range borders the north-western end of Lake Tekapo. A relatively flat area, consisting of moraine and outwash deposits, opens up to the south of the Hall and neighbouring ranges, making up the plains of the Mackenzie Basin. This landscape borders the western and southern sides of Lake Tekapo. Within the hummocky terrain immediately west of Lake Tekapo lies Lake Alexandrina, which is completely enclosed by moraine and outwash deposits associated with the formation of Lake Tekapo.

The slopes around Lake Tekapo are very steep, except where small benches have been cut (Graham *et al.*, 2005). These slopes give way to a relatively flat lakebed with a maximum depth of 120 m. The Godley delta occupies the northern end of the lake and the lakebed grades gently down to the area of maximum depth approximately 18 km away (Irwin & Pickrill, 1982). From the area of maximum depth, just east of Motuariki Island, the lakebed of Lake Tekapo slopes gently upwards to the southern shores of the lake.

2.6 Chapter Summary

- The landscapes surrounding Lakes Lyndon, Coleridge and Tekapo have been shaped by geological, geomorphological and climate processes over millions of years. The basement rocks of Canterbury consist mainly of the Torlesse Supergroup, an extensive sedimentary deposit, which formed between 520 to 110 Ma. More specifically, Lakes Lyndon, Coleridge and Tekapo lie within the

Rakaia Terrane, which consists primarily of a quartzofeldspathic, sandstone to mudstone association. The south-west region of the Rakaia Terrane grades laterally into its metamorphosed contingent, the Haast Schist, which outcrops in small amounts to the east of Lake Tekapo. Following separation of New Zealand from Gondwanaland around 85 Ma, a new set of deposits was laid down on top of the Torlesse Supergroup rocks. However, due to extensive erosion from glacial processes during the Quaternary, only sparse remnants of these cover sequences exist around each of the lakes.

- There are well-preserved glacial deposits around Lakes Coleridge and Tekapo. It is not known whether or not Lake Lyndon was occupied by ice. The formation of Lake Lyndon itself occurred as a result of damming of the local drainage by alluvial fans, which surround the lake today. Four major ice advances occurred at Lake Coleridge. The surficial glacial deposits, which are present around the lake today, have been attributed to the last major advance, the Acheron Advance, which occurred approximately 10,000 to 14,000 years ago. During this advance, two distinct ice streams are believed to have been present. Other than the well-documented Rakaia Glacier, another major glacier, the Coleridge/Wilberforce Glacier occupied the trough in which Lake Coleridge lies today. Like Lake Coleridge, the landscape around Lake Tekapo is also primarily the result of glaciation. The Godley Glacier, of which only a small remnant exists today, concealed the lake and its surroundings for much of the Pleistocene. Moraines from subsequent advances effectively dammed the valley, which led to the formation of the lake.

- About 14,000 years ago, global temperatures started to increase, causing worldwide glacial recession. As a result, the landscape began to make major readjustments. Numerous ice drainage systems were abandoned and many of the streams around the lakes altered their courses. Adjustment of surrounding rock slopes also occurred as lateral support once provided by the ice was removed.

- Earthquake, landslide and climate processes continue to shape the land today. These processes can severely threaten areas of development, which have been built in vulnerable areas. Therefore in order to prevent potential disasters occurring, an understanding of these processes and recognition of vulnerable areas must be made.

CHAPTER 3 -

THE SOCIAL ENVIRONMENT OF LAKES LYNDON, COLERIDGE AND TEKAPO

In order to carry out a hazard assessment of a particular place, it is important to not only understand its physical setting, but also its social setting. For example, it is important to identify tourism and population trends in order to understand how fast an area is expected to grow. It is also important to identify areas most likely to experience intense development and this is primarily governed by land ownership. This chapter therefore outlines the current development and population at Lakes Lyndon, Coleridge and Tekapo, summarises population and tourism trends for Canterbury, and identifies specific areas around each of the lakes with the most potential for development.

3.1 New Zealand Population Trends and Likely Future Growth

The population of New Zealand has been increasing steadily over the last half century (Figure 3.1). According to the 2006 census, the usual resident population of New Zealand (a count of all people present on a census night and who usually live in New Zealand) reached 4.028 million, an increase of 7.8 per cent since the 2001 census (Statistics New Zealand, 2006). Recently, the total New Zealand population, which includes visitors, has been increasing at an average rate of almost 2 per cent per year (Baxendine, 2005). This rate is likely to decrease to about 0.8 per cent per year over the next nine years or so, leading to a population of about 4.5 million in 2016 (ibid). This predicted decrease in the average yearly rate of growth has been attributed to the narrowing gap between births and deaths. With this in mind, Statistics New Zealand predicts that the population will reach 5.05 million by 2051.

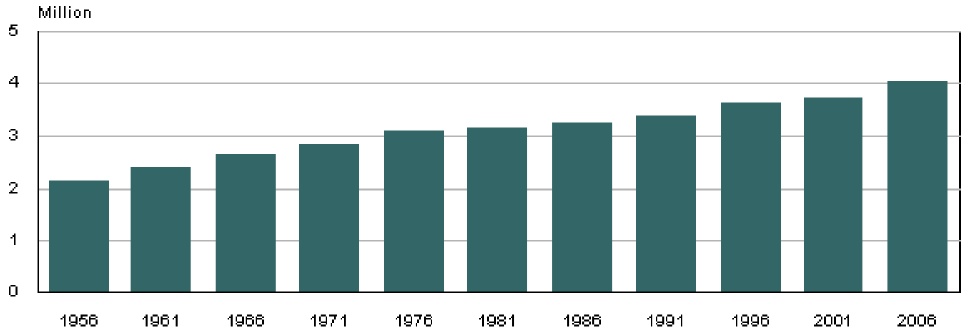

Figure 3.1: The increasing trend of New Zealand's usually resident population from 1956 to 2006 censuses. Source: Statistics New Zealand.

3.1.1 Canterbury Population Trends and Likely Future Growth

Population trends at a national level may not always be indicative of population changes at a regional level; even within a region, such as Canterbury, many different trends may be occurring in different places. Information within this section has been largely acquired from Statistics New Zealand.

The South Island is home to approximately 24 per cent of New Zealand residents, with 53.9 per cent of these residing in Canterbury. The 2006 South Island population of 967,910 grew by 6.7 per cent between 2001 and 2006 with Canterbury growing by about 8 per cent, just higher than the national average. The usually resident population of Canterbury according to the 2006 census was 521,832. Just as the national population is projected to have a slowing rate of growth in the near future, so is Canterbury. Despite this, between 2001 and 2026, Canterbury's population is projected to increase by about 18 per cent to about 584,400, and is expected to have the second highest numerical growth in population, after the Auckland region. Most of this numerical growth will occur in the Christchurch territorial area.

3.1.1.1 Lakes Lyndon and Coleridge

Lakes Lyndon and Coleridge lie within the Selwyn District of Canterbury, and more specifically within the Malvern Area Unit (Figure 3.2). The Selwyn District had a usually resident population count of 33,666 in the 2006 census, experiencing a 23.3 per cent population increase since the 2001 census. This district experienced the second highest intercensal rate of population growth in the country after the Queenstown-Lakes District, which grew by 34.7 per cent. Between 2001 and 2026 the Selwyn District is projected to grow by a further 57 per cent, with most of this growth attributed to net migration gains. According to Table 3.1, the biggest growth areas within the Selwyn District appear to be Rolleston, Prebbleton, Springston and West Melton. Therefore most of the growth expected up until 2026 will probably continue to be concentrated in these areas. Malvern appears to have one of the lowest growth rates in the district. However, Lake Coleridge appears to be attracting a lot of interest from developers and any further development would ensure a steady population increase in the area.

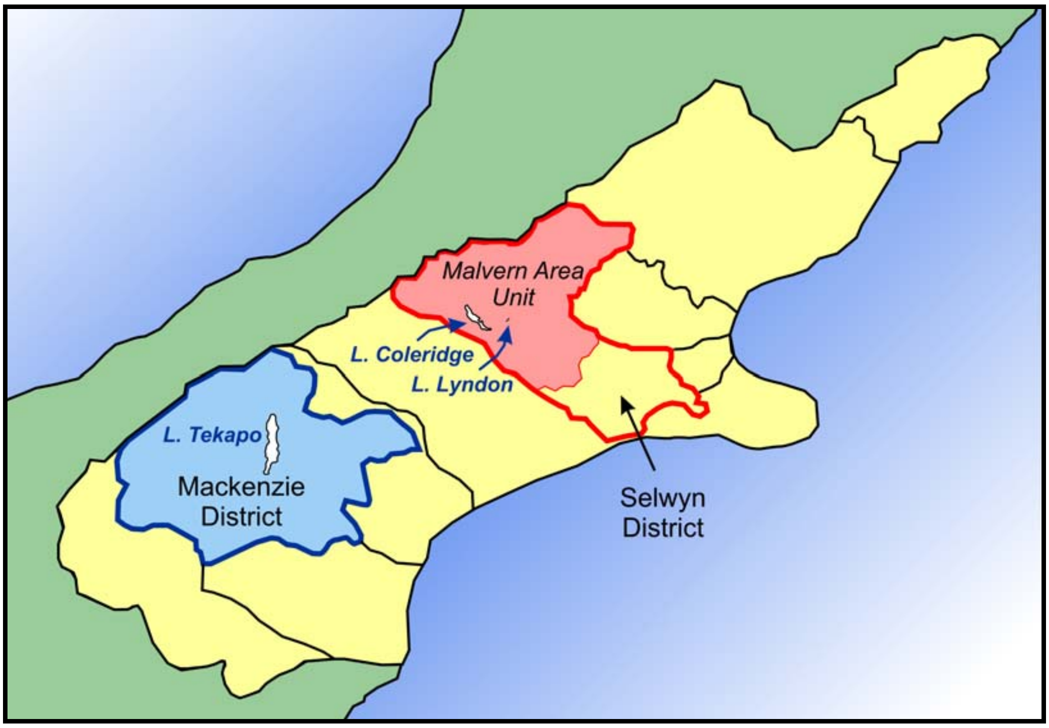

Figure 3.2: The location of the Mackenzie District, Selwyn District and the Malvern Area Unit within Canterbury (shaded in yellow).

Table 3.1: Census Usually Resident Population Counts and Intercensal Population Changes (IPC) for Area Units within the Selwyn District Council for the period 1981-2006. Source: Statistics New Zealand.

Area Unit	1996 Census Usually Resident Population Count	Intercensal Population Change (%)	2001 Census Usually Resident Population Count	Intercensal Population Change (%)	2006 Census Usually Resident Population Count
Darfield	1,299	8.1	1,404	5.6	1,482
Kirwee	2,253	17.3	2,643	14.6	3,030
Burnham Military Camp	1,464	22.3	1,137	6.1	1,206
Malvern	***2,514***	***3.1***	***2,592***	***5.8***	***2,742***
Prebbleton	1,674	9.7	1,836	64.7	3,024
West Melton	4,113	13	4,647	20.8	5,613
Taitapu	453	-7.9	417	-1.4	411
Lincoln	2,319	-7.6	2,142	27.3	2,727
Leeston	1,233	-2.4	1,203	8	1,299
Southbridge	675	6.7	720	2.1	735
Rolleston	1,050	88	1,974	93.6	3,822
Dunsandel	387	3.9	402	7.5	432
Springston	2,607	16.7	3,042	21	3,681
Inland Water-Lake Ellesmere North	-	-	-	-	-
Selwyn-Rakaia	2,748	15	3,159	9.6	3,462
TOTAL	**24,783**	**10.2**	**27,312**	**23.3**	**33,666**

3.1.1.2 Lake Tekapo

Lake Tekapo lies within the Mackenzie District (Figure 3.2), which unlike the Selwyn District only experienced a 2.3 per cent increase in population since the 2001 census. The usually resident population of the district was 3804 according to the 2006 census. Projections actually show a possible decrease in the population of the district by about 6 per cent between 2001 and 2026 to an estimated population of about 3600. However, this trend is not likely to occur within the Lake Tekapo rural community. Table 3.2

shows the population changes within the Mackenzie District compared to that of the Tekapo rural community. Even though the Mackenzie District as a whole experienced a decrease in population of 8.8 per cent between 1996 and 2001, the population within Tekapo increased by 3.1 per cent and again by four per cent between 2001 and 2006. The population within the rural community will most likely continue to increase steadily. Looking into the future, development at Tekapo is flourishing, but mostly for tourists.

Table 3.2: Census Usually Resident Population Counts and Intercensal Population Changes (IPC) for the Mackenzie District and Lake Tekapo for the period 1981-2006. Source: Statistics New Zealand.

	1981	IPC (%)	1986	IPC (%)	1991	IPC (%)	1996	IPC (%)	2001	IPC (%)	2006
Mackenzie District	6882	-40.3	4110	-17.7	3381	+20.6	4077	-8.8	3717	+2.3	3804
Lake Tekapo	240	+7.5	258	-39.5	156	+88.5	294	+3.1	303	+4	315

3.2 New Zealand Tourism Trends

Tourism can have a direct impact on the growth of a region both short-term and long-term, so it is important to consider these trends alongside resident population trends at a national and regional scale. According to Tourism New Zealand, tourism has become the country’s largest employer and largest foreign exchange earner, with NZ$8.6 billion generated in 2006 (Tourism New Zealand, 2007). The Ministry of Tourism has forecast excellent long-term prospects for the tourism industry and it is vital that these forecasts are considered in any development and emergency management planning. Tourism forecasts will be drawn from the latest Ministry of Tourism forecasts, 2007 to 2013 (New Zealand Ministry of Tourism & Tourism Research Council New Zealand, 2007). These forecasts must, however, be taken cautiously as there are a number of factors which may affect their inaccuracy, including data limitations and political and/or economic factors that could influence international travel, agriculture and recreation.

International visitor arrivals have been steadily increasing over the last few decades, reaching an all-time high of 2.41 million in 2006. Total arrivals are expected to increase by about 4 per cent per annum to 3.17 million by 2013. Together, domestic and international visitor nights are forecast to increase by 2.3 per cent per annum from 99.2 million in 2006 to 116 million in 2013. For the purposes of this study, the likely tourism trends within Canterbury are of interest.

New Zealand is split into 29 Regional Tourism Organisations (RTO’s), which in most instances follows Territorial Authority boundaries. The Canterbury RTO covers a geographic area that includes three other RTO’s – Hurunui, Central South Island and Mackenzie. According to the March 2008 Tourism Leading Indicators Monitor, all 29 RTO’s are expected to experience tourism increases between now and 2013.

3.2.1 Canterbury Tourism Trends

Canterbury is a very popular tourist destination. Total visits by international and domestic visitors are expected to increase 16.4 per cent from 10.7 million in 2006 to 12.03 million in 2013. The forecasts for day and overnight visits for all Regional Tourism Organisations are presented in Table 3.3. In terms of day visits, the Canterbury RTO is expected to experience a growth of 9.7 per cent between now and 2013. More specifically the Mackenzie RTO is forecast to grow significantly (16.3 per cent) in day visits, which is one of the highest rates in the country. Overnight visits in the Canterbury RTO are expected to increase by 15.2 per cent, from 4.7 million in 2006 to 5.4 million in 2013. Overnight visits in the Mackenzie RTO are forecast to increase by 16.5 per cent. Both day and overnight visit forecasts for the Canterbury and Mackenzie RTO’s are higher than the expectations for New Zealand as a whole.

Table 3.3: Forecasts of Day and Overnight Visits by RTO ('000s). Source: New Zealand Ministry of Tourism & Tourism Research Council, (2007): 31.

Destination	Day Visit Forecasts					Overnight Visit Forecasts				
RTO	2006	2013	Change	Total	Annual	2006	2013	Change	Total	Annual
Northland	2,714	2,980	266	9.8%	1.3%	1,774	2,018	243	13.7%	1.9%
Auckland	7,243	7,998	755	10.4%	1.4%	4,849	5,715	866	17.9%	2.4%
Coromandel	1,214	1,345	131	10.8%	1.5%	1,213	1,339	126	10.4%	1.4%
Waikato*	5,938	6,534	596	10.0%	1.4%	1,810	1,979	169	9.3%	1.3%
Bay of Plenty	1,831	1,970	138	7.6%	1.0%	1,369	1,485	116	8.5%	1.2%
Rotorua	1,409	1,542	133	9.5%	1.3%	1,484	1,790	305	20.6%	2.7%
Lake Taupo	970	1,066	96	9.9%	1.4%	1,248	1,380	133	10.6%	1.5%
Kawerau-Whakatane*	513	547	34	6.6%	0.9%	280	306	26	9.3%	1.3%
Eastland	350	359	9	2.6%	0.4%	402	434	32	7.9%	1.1%
Taranaki	899	913	14	1.6%	0.2%	639	689	50	7.9%	1.1%
Hawke's Bay	941	974	33	3.5%	0.5%	1,088	1,181	93	8.5%	1.2%
Ruapehu	383	412	28	7.4%	1.0%	405	445	40	9.8%	1.3%
Manawatu	2,114	2,178	63	3.0%	0.4%	728	770	42	5.7%	0.8%
Wanganui	508	518	10	2.0%	0.3%	288	311	23	8.0%	1.1%
Wairarapa	948	1,006	57	6.1%	0.8%	299	319	20	6.5%	0.9%
Kapiti-Horowhenua	1,903	2,003	100	5.2%	0.7%	381	402	20	5.3%	0.7%
Wellington	2,063	2,189	126	6.1%	0.9%	2,270	2,531	261	11.5%	1.6%
Marlborough	415	465	49	11.8%	1.6%	683	777	94	13.8%	1.9%
Nelson	1,019	1,128	109	10.7%	1.5%	945	1,085	141	14.9%	2.0%
Canterbury	6,057	6,643	586	9.7%	1.3%	4,673	5,385	711	15.2%	2.0%
Hurunui	545	595	51	9.3%	1.3%	357	398	41	11.4%	1.5%
Central South Island	733	796	64	8.7%	1.2%	326	361	36	10.9%	1.5%
Mackenzie	431	501	70	16.3%	2.2%	446	519	73	16.5%	2.2%
Waitaki	444	487	43	9.8%	1.3%	316	359	43	13.7%	1.9%
West Coast	685	787	103	15.0%	2.0%	1,221	1,476	255	20.9%	2.7%
Lake Wanaka	139	164	25	18.3%	2.4%	446	515	70	15.6%	2.1%
Queenstown	250	310	60	23.8%	3.1%	1,090	1,317	226	20.8%	2.7%
Central Otago	317	341	24	7.6%	1.1%	313	334	22	6.9%	1.0%
Dunedin	654	704	51	7.8%	1.1%	927	1,066	139	15.0%	2.0%
Clutha*	637	673	37	5.7%	0.8%	157	168	11	7.2%	1.0%
Fiordland	484	602	118	24.4%	3.2%	468	583	115	24.7%	3.2%
Southland	976	1,015	38	3.9%	0.6%	497	557	59	11.9%	1.6%
New Zealand	**44,017**	**47,851**	**3,834**	**8.7%**	**1.2%**	**32,264**	**36,716**	**4,452**	**13.8%**	**1.9%**

* Currently not a funded RTO.

3.3 Current Development and Population around Lakes Lyndon, Coleridge and Tekapo

Lakes Lyndon, Coleridge and Tekapo all have different populations and levels of development (infrastructure and housing). The land around Lake Lyndon is virtually undeveloped whereas the areas around Lakes Coleridge and Tekapo are moderately developed.

3.3.1 Lake Lyndon

There is minimal development around Lake Lyndon and therefore there are no permanent residents. A gravel road (Lyndon Road) runs along its eastern side, connecting State Highway 73 to Lake Coleridge (Figure 3.3). This is one of two ways to get to Lake Coleridge and is therefore reasonably popular. Telephone lines extend along the eastern side of the road. Lake Lyndon Lodge, which is available for hiring, is situated at the lake's southern end and a small shelter is located at the northern end of the lake.

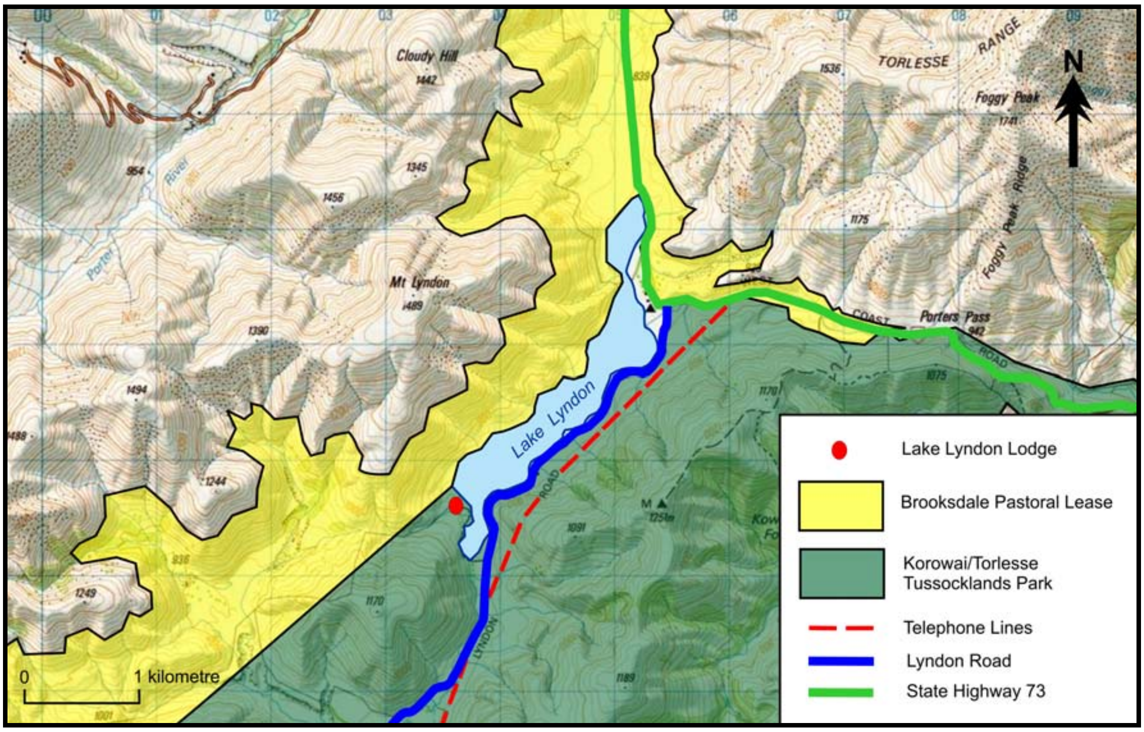

Figure 3.3: Development and land allocation around Lake Lyndon. Land allocation boundaries are approximate only.

3.3.2 Lake Coleridge

There is a reasonable amount of development around Lake Coleridge. The area first really became developed in the early 1900's when the country's first major hydro-electric power station was built on the southern side of the lake (Figure 3.4). Subsequently a small village developed next to the station to accommodate the workers and their families (Britten, 2000). The Lake Coleridge Village is still well established today. However, as the station no longer requires the large workforce it once had, the population of Coleridge Village has been decreasing. It now consists mainly of holiday and retirement homes. There are approximately thirty usually resident people in the area (Selwyn District Council, 2005). However, the amount of people in the area can increase immensely during peak tourist seasons, to approximately 200 to 300 people.

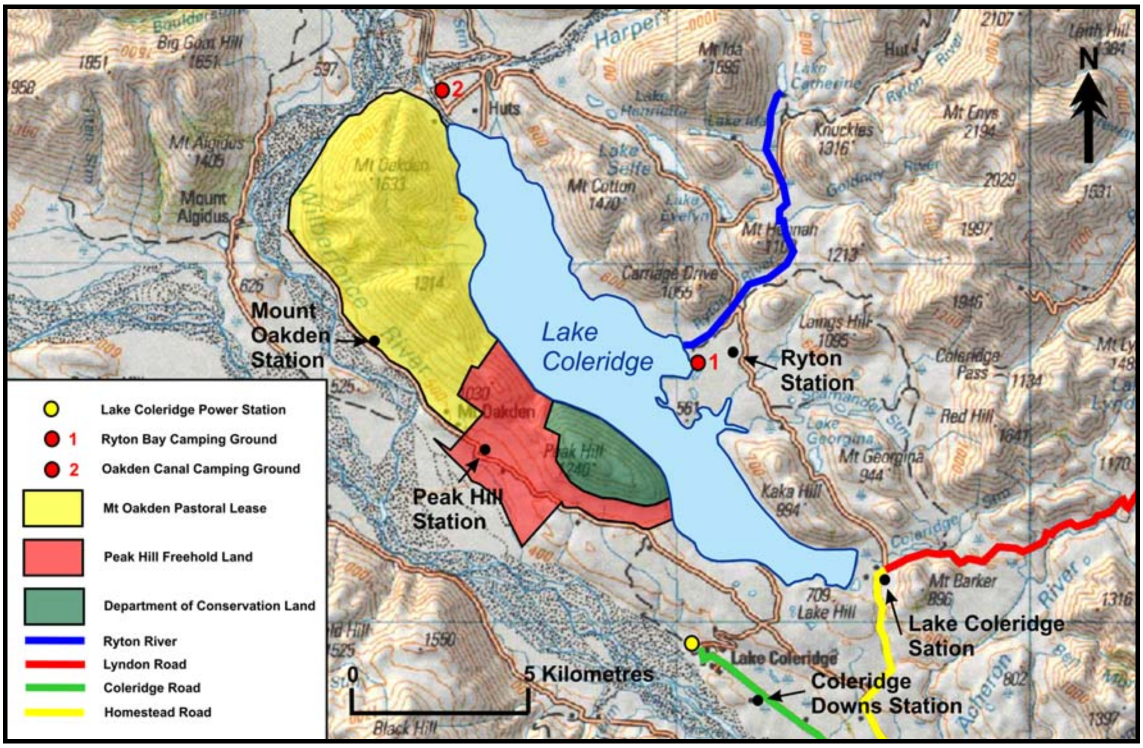

Figure 3.4: Development and land allocation around Lake Coleridge. Land allocation boundaries are approximate only.

The Lake Coleridge area has been used for sheep farming for more than 150 years, and continues to be prosperous. There are a number of farming stations immediately around the lake including Ryton, Lake Coleridge, Coleridge Downs, Peak Hill and Mount Oakden Stations (Figure 3.4). There are two main camping grounds bordering the lake, both of which have permanent structures. The larger of the two, Ryton Bay Camping Ground, is situated adjacent to the mouth of the Ryton River and the smaller, Oakden Canal Camping Ground, is located on the Harper Fan, at the base of Mount Oakden. There are two main roads leading to Lake Coleridge. The first route is via Lyndon Road and the other via Coleridge and Homestead Roads.

3.3.3 Lake Tekapo

Lake Tekapo is the most developed of the three lakes in this study, and has the largest population. Like Lake Coleridge, the region was first used for farming and today the lake is surrounded primarily by farming stations, thousands of hectares in size. These stations include Mount Gerald, Richmond, Mount Hay, Glenmore and Godley Peaks

(Figure 3.5). Lake Tekapo is also a significant tourist destination, with an expanding township at the lake's southern end. New housing and accommodation development is continuously occurring. Other significant development in the area includes an astronomical observatory situated on Mt John, and the Tekapo power station. The lake was considered an ideal site for a hydro-electric power station in the 1930's and is today part of the extensive Upper Waitaki power scheme. Control gates were constructed across the Tekapo River, which runs through the centre of the township and the power station (Tekapo A Power Station) is located just south of the township.

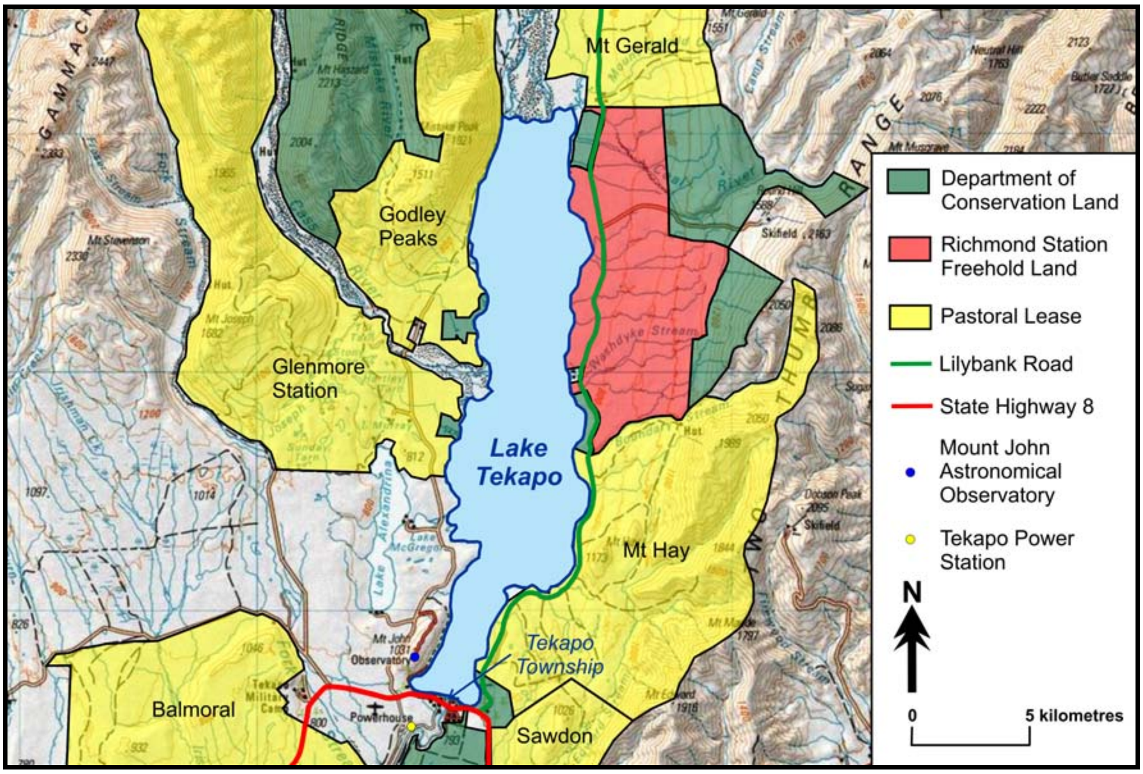

Figure 3.5: Development and land allocation around Lake Tekapo. Land allocation boundaries are approximate only.

At the 2006 census, the usually resident population of Lake Tekapo was 315. However, the overnight population can more than double due the numbers of visitors in the area; on the night of the 2006 census, there were 816 people present. The weekend population also increases significantly due to the number of holiday homes in the area.

3.4 Areas of Possible Future Development

In this study, the areas around Lakes Lyndon, Coleridge and Tekapo that have a high possibility of being intensely developed in the future, are of interest. Land is generally divided into freehold or Crown-owned land, and it is the freehold land that is much more likely to have development occur. Most of the land around the lakes is Crown-owned and leased out to farmers. However, under the Crown Pastoral Land Act 1998, farmers can decide to have their lease reviewed through a process called Tenure Review, with the opportunity for a lot of their lease land to become freehold. This process and its implications for the lake areas are described.

3.4.1 Tenure Review

Canterbury lakes located directly on the eastern side of the Southern Alps, such as the lakes within this study, are mostly surrounded by High Country land. This land has been leased by the Crown to South Island farmers for pastoral farming purposes for more than a century. It is currently the last mass of unallocated Crown land within New Zealand to be divided into private and full Crown ownership through the Tenure Review, under the Crown Pastoral Land Act 1998. In general, the Tenure Review allows leaseholders to gain freehold title of part of their leasehold land. The rest of the land, which is generally land recognised for its significant inherent values, is retained by the Crown and managed by the Department of Conservation (DoC). The Tenure Review process also ensures an improvement of public access to the High Country. Once a leaseholder has gained freehold title of their land, they are free to diversify into economic activities other than grazing, such as viticulture, forestry, subdivision and ecotourism.

However, in June 2007, the government called a halt to Tenure Review of lakeside properties in the High Country in order to protect these areas from inappropriate subdivision and development. All lakes larger than 5 km^2 within the High Country were considered and as a result, 65 lakeside properties within 5 km and visible from these lakes were identified. The Crown withdrew from Tenure Review on a lot of these properties. However, even though the process was halted for many properties, it does not mean that they will never be eligible to complete the process. They may be considered if the lessee is prepared to meet certain conditions, such as allowing land to be retained by the Crown or accepting restrictions on the land's future use and development. Of the 65 lakeside properties identified, one of these is by Lake Coleridge and six are around Lake Tekapo. With this in mind, future development possibilities at each of the lakes are considered.

3.4.2 Future Development at Lake Lyndon

Lake Lyndon is one of the most accessible lakes in the region due to its location next to SH73 just over Porters Pass, approximately one hour from Christchurch. This makes the lake a popular site for recreational purposes, such as fishing. Approximately half of the land around the lake is part of the Korowai/Torlesse Tussocklands Park, which is administered by the Department of Conservation (DoC) (Figure 3.6). Therefore this area is protected for recreational purposes and it is unlikely that any intense development would be allowed. If any type of development were to occur, it would have to be strongly linked to recreation or conservation purposes. The other half of land surrounding Lake Lyndon is part of the Brooksdale pastoral lease, which is able to go through Tenure Review. Although it is not currently going through the process, some preliminary work has been done and there is a recommendation that the lease-land around the lake (Figure 3.6) should be retained by the Crown and administered by DoC. Therefore, if any development were to occur around Lake Lyndon, it would most likely be on DoC land to the north and south of the lake.

3.4.3 Future Development at Lake Coleridge

Lake Coleridge is also a popular recreation location. The land surrounding the lake is divided into pastoral lease, Crown conservation, and privately owned land (Figure 3.7). Mt Oakden pastoral lease was recently included within the 65 lakeside properties in which the government called a halt to Tenure Review. Therefore this area is protected from any major development, such as subdivision, occurring and will most probably be continued to be used for farming purposes.

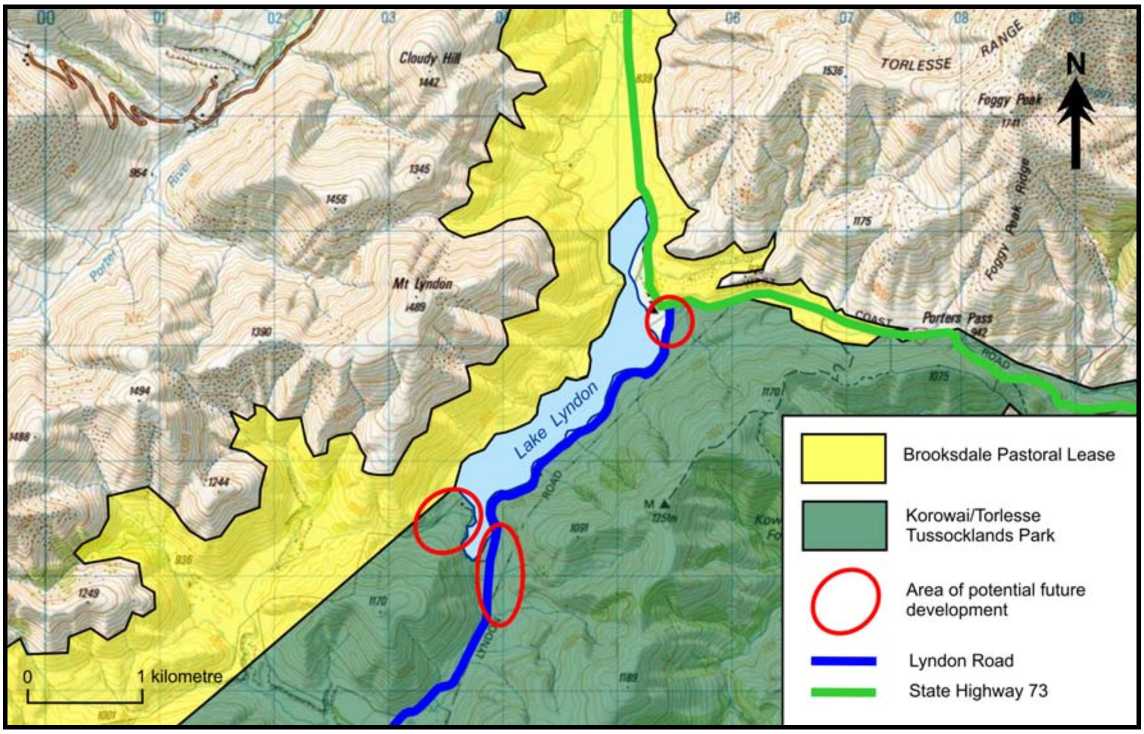

Figure 3.6: Land allocation and the most likely area for future development around Lake Lyndon. Land allocation boundaries are approximate only.

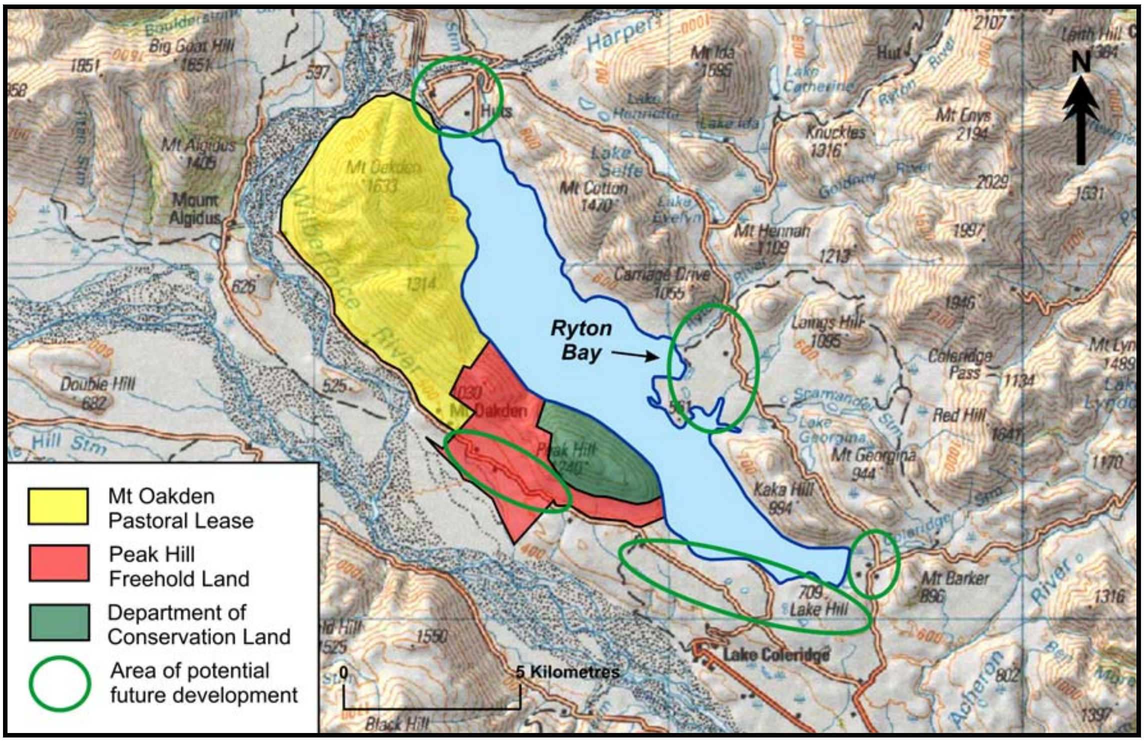

Figure 3.7: Land allocation and the most likely areas for future development around Lake Coleridge. Land allocation boundaries are approximate only.

Another pastoral lease, Peak Hill, completed the Tenure Review in March 2006, before the government's decision regarding lakeside property. As a result, about 600 ha were converted into conservation land now administered by the Department of Conservation, and the remaining c. 1000 ha became freehold. Therefore there is potential for this freehold area to be subdivided and intensely developed. The rest of the land around Lake Coleridge, including its entire eastern and southern end is privately owned. The majority of this area is used for farming purposes but there is potential for further development. For example there has been huge interest in developing the Ryton Bay area, which was recently sold. There are plans to divide 50 ha of land next to the lake into 232 sections, including the development of a 100-site camping ground. However, there are no definite plans yet.

3.4.4 Future Development at Lake Tekapo

The majority of land around Lake Tekapo is pastoral lease. A small amount of public conservation land lies to the south-east of the lake and the rest of the land immediately south and south-west of the lake is privately owned. One of the pastoral leases, Richmond, completed the Tenure Review process before the government called a halt to Tenure Review of lakeside properties. 3,630 ha of Richmond were subsequently retained by the Crown, with the remaining 5,948 ha becoming freehold. There is potential for the freehold land to be intensely developed (Figure 3.8). Balmoral, Glenmore Station, Godley Peaks, Mt Gerald, Mt Hay and Sawdon are among the 65 properties now protected from development, such as subdivision, and will most likely continue to be used for farming purposes. Therefore, there are great development prospects for the privately owned land around the Tekapo Township, the coastal area north of Mount John, and for the freehold land of Richmond Station.

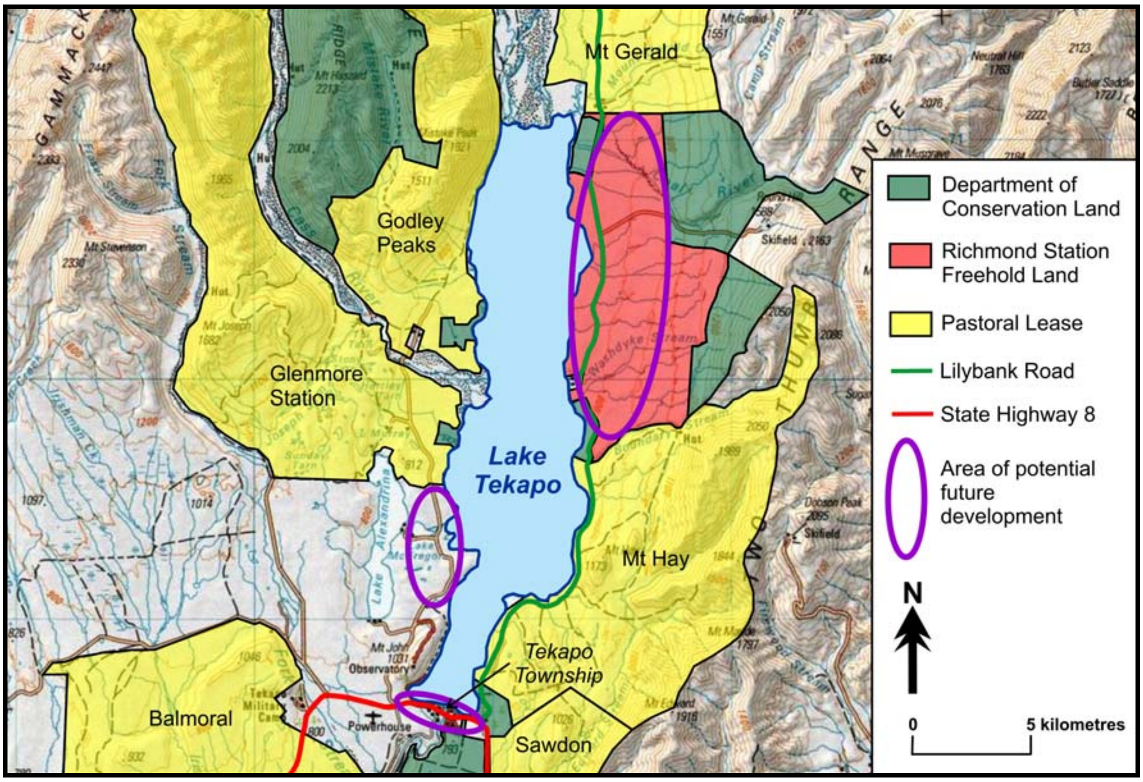

Figure 3.8: Land allocation and the most likely areas for future development around Lake Tekapo. Land allocation boundaries are approximate only.

3.5 Chapter Summary

- Population trends for Canterbury suggest that significant growth is expected in the future, especially for the Selwyn District in which Lakes Lyndon and Coleridge lie. However, most of the growth within this district is expected to occur within 20 km of Christchurch and therefore not directly around the lake areas. There are currently no permanent residents around Lake Lyndon and this area will most likely remain unpopulated. There are approximately 30 residents around Lake Coleridge, which has experienced a population decline. However there is huge interest in developing around Ryton Bay and if this were to occur the population would increase.

- Lake Tekapo lies within the Mackenzie District, which is actually forecast to experience a population decrease over the next fifteen or so years. However, the population at the Tekapo Township has been generally increasing and will most likely continue to do so. Overnight visits by tourists in to Canterbury are also expected to increase significantly, especially in the Mackenzie District. These trends, along with population growth are expected to drive development within Canterbury.

- There is huge potential to develop around Lakes Coleridge and Tekapo. The areas with the most potential for development around Lake Coleridge include the land to the east of the lake, especially around Ryton Bay, the Harper Fan area, and the area to the south-east of Peak Hill. The areas with the most potential for development around Lake Tekapo include around the existing Tekapo Township, the freehold land of Richmond Station and the land to the north of Mount John, on the shores of Lake Tekapo. Lake Lyndon will most likely be kept free of development due to the land around the lake being administered by the Department of Conservation. However, there is still potential for development linked with recreational and conservation purposes to occur.

- As development increases around the lake areas, the risk from natural hazards, which may threaten these areas, increases. Therefore, it is imperative that any potential hazards are recognised before development occurs so that appropriate measures can be taken. In areas where development has already occurred, the threat from hazards must be reduced as much as possible.

CHAPTER 4 –
EARTHQUAKE HAZARDS

4.1 Introduction

Countless earthquakes have shaken New Zealand throughout its history and will continue to do so into the future. New Zealand's seismicity is due to its location on the active boundary between the Australian and Pacific tectonic plates, which are converging at c. 40 mm per year. Between 10,000 to 15,000 earthquakes are recorded in and around New Zealand each year, with up to 200 of those large enough to be felt (McSaveney & Nathan, 2007). The seismic threat to Canterbury is significant, especially as development pressures increase and encroachment of development to the vicinity of active faults occurs.

A comprehensive earthquake hazard and risk assessment study for the Canterbury region was initiated by Environment Canterbury in 1997 (Kingsbury *et al.*, 2001). Over the last ten years, extensive studies have been undertaken in response to this. Notable studies include those by Pettinga *et al.* (1998), Stirling *et al.* (1999), Kingsbury *et al.* (2001), Pettinga *et al.* (2001), Stirling *et al.* (2001), Stirling *et al.* (2002), Yetton and McCahon (2006), and Stirling *et al.* (2007). The majority of information within this chapter is derived from these papers. This chapter, therefore, seeks to identify seismic sources relevant to Lakes Lyndon, Coleridge and Tekapo and to summarise the risk to these areas.

4.2 Active Tectonic Setting of Canterbury

New Zealand is situated on the active boundary between the Australian and Pacific tectonic plates (Figure 4.1). The motion between these two plates has determined the development of the New Zealand landmass over the last c. 5 to 10 million years and is directly responsible for the seismicity within the country (Pettinga *et al.*, 2001).

Subduction of the Pacific Plate beneath the Australian Plate occurs to the east of the North Island and a transition to collision between the two plates occurs in North Canterbury. The rest of the Canterbury region is dominated by the ongoing, oblique collision of the two plates, which has formed an extensive zone of active earth deformation, characterised by crustal thickening, uplift and faulting (Figure 4.2) (Pettinga *et al.*, 2001). Between 70 to 75 per cent of the interplate boundary motion is accommodated by the Alpine Fault, an east-dipping, oblique, strike-slip fault, which trends north-east to south-west to the west of Canterbury (Figure 4.1) (Norris & Cooper, 2000; Pettinga *et al.*, 1998). The rest of the oblique plate motion is dispersed among faults in the northern, central and southern parts of the region (Stirling *et al.*, 2007). Large and relatively frequent earthquakes are capable of being produced within Canterbury and due to its large geographic extent, a large earthquake produced anywhere in the South Island is capable of significantly impacting the area (Pettinga *et al.*, 2001).

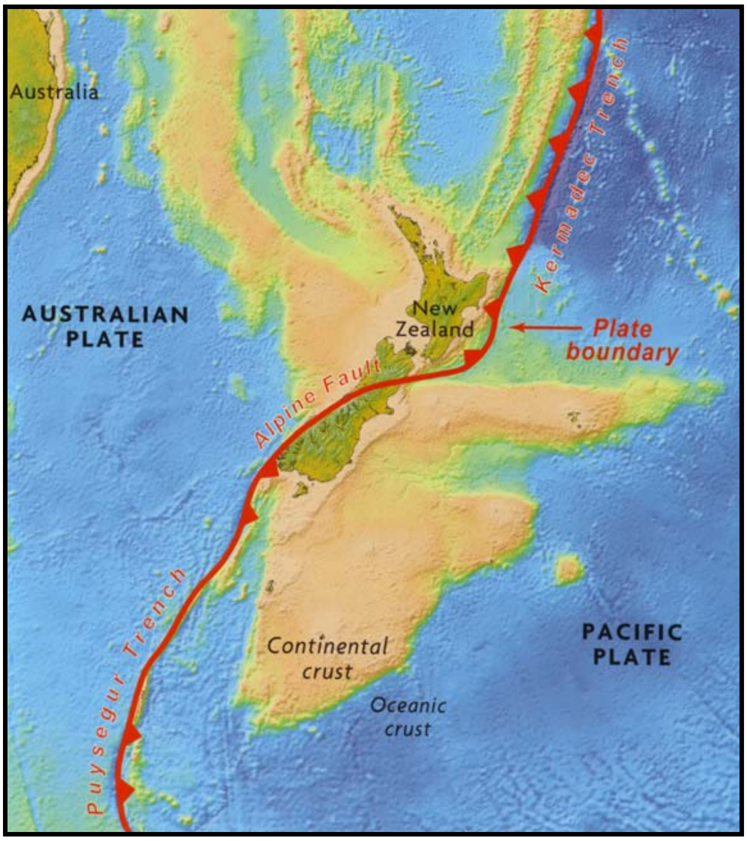

Figure 4.1: The active boundary (red line) between the Australian and Pacific plates. Source: McSaveney, (2007): 31.

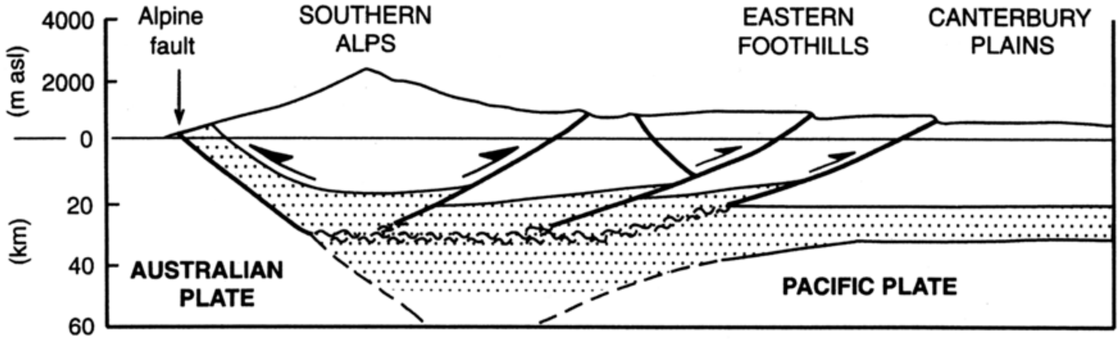

Figure 4.2: Schematic diagram of the oblique continent-to-continent collision zone of the Australia-Pacific plate boundary across the central South Island. Shading represents lower crustal rocks. Source: Pettinga *et al*., (2001): 286.

The seismic hazard within Canterbury decreases from the north-west to the south-east due to varying levels of crustal deformation activity (Figure 4.3) (Pettinga *et al.*, 2001). The northern part of Canterbury is characterised by north-east trending strike-slip and oblique strike-slip faults (ibid). These faults are responsible for transferring the plate motion from the Alpine Fault to the Hikurangi Trench. Recurrence intervals for earthquakes on the northern faults range from c. 81 to >5000 years. The central and southern parts of Canterbury are characterised by predominantly north-trending, oblique-reverse and reverse/thrust faults with recurrence intervals ranging from c. 2500 to >20,000 years (ibid).

Significant damage to the areas immediately surrounding each of the lakes in this study could occur on a range of scales. Firstly, significant damage could result from low to moderate magnitude (up to M 6.5 to 7) events produced by near-field faults (within 15 km) at depths of 10 to 15 km. Surface rupture does not necessarily need to occur. Secondly, significant damage can also be produced by medium to large faults located up to 100 km from the lakes. Any earthquake produced at a distance of more than 100 km from the lake areas is only likely to impact, if at all, very vulnerable areas such as artificial fills and areas underlain by very soft sediments (Yetton & McCahon, 2006). Therefore, potential earthquake sources will be dealt with in two parts. Firstly, local active faults within 15 km of the lakes will be examined. Then, medium to large active faults that lie within 50 to 100 km of the local faults will be considered.

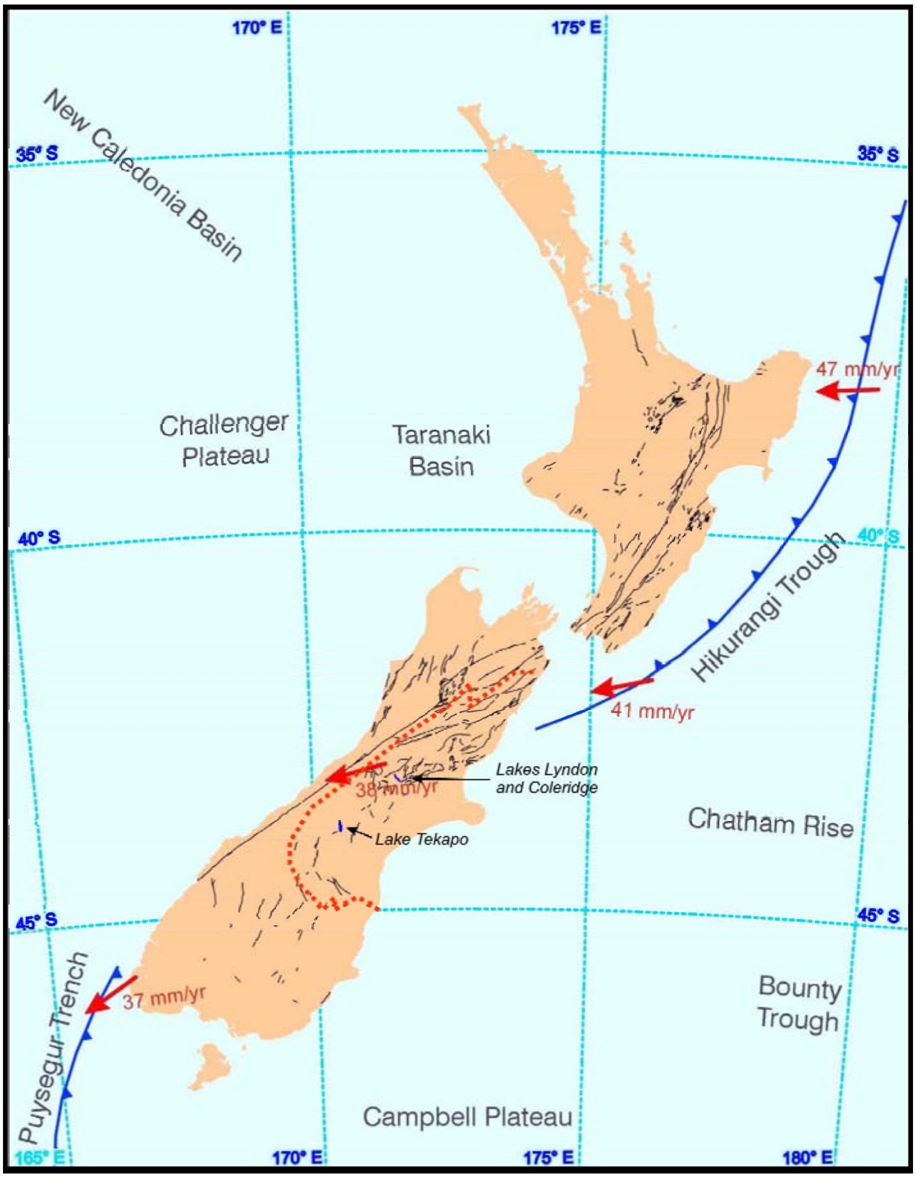

Figure 4.3: Active fault traces within New Zealand. The approximate boundary of the Canterbury Region is indicated by the red dotted line. There is an overall decrease in the amount of crustal deformation activity (and active faults) from north to south Canterbury. Source: Adapted from Stirling *et al.,* (2007).

4.3 Active Faults in the Vicinity of Lakes Lyndon and Coleridge

A large number of faults have been identified in the Lake Lyndon and Coleridge area, with the majority of them trending in either an east-north-east or north-north-west direction. A handful of these faults has been studied extensively, and their seismic properties, such as recurrence intervals and slip rates, have been identified. However, most faults in the area have not been studied in depth and their seismic properties remain unknown. Further research is, therefore, required to determine their seismic properties.

4.3.1 Local Earthquake Sources

There are numerous significant active faults surrounding Lakes Lyndon and Coleridge. The most serious threat comes from the Porters Pass Fault, which crosses through both lakes. Work carried out on the Porters Pass Fault, along with other faults in the area, has shown that most of them are capable of generating earthquakes with magnitudes of M_w7 or greater. A summary of active faults with their identified seismic characteristics is provided in Table 4.1. There are also numerous unnamed active faults within the region that must also be considered as possible seismic sources despite their seismic properties remaining unknown (Figure 4.4).

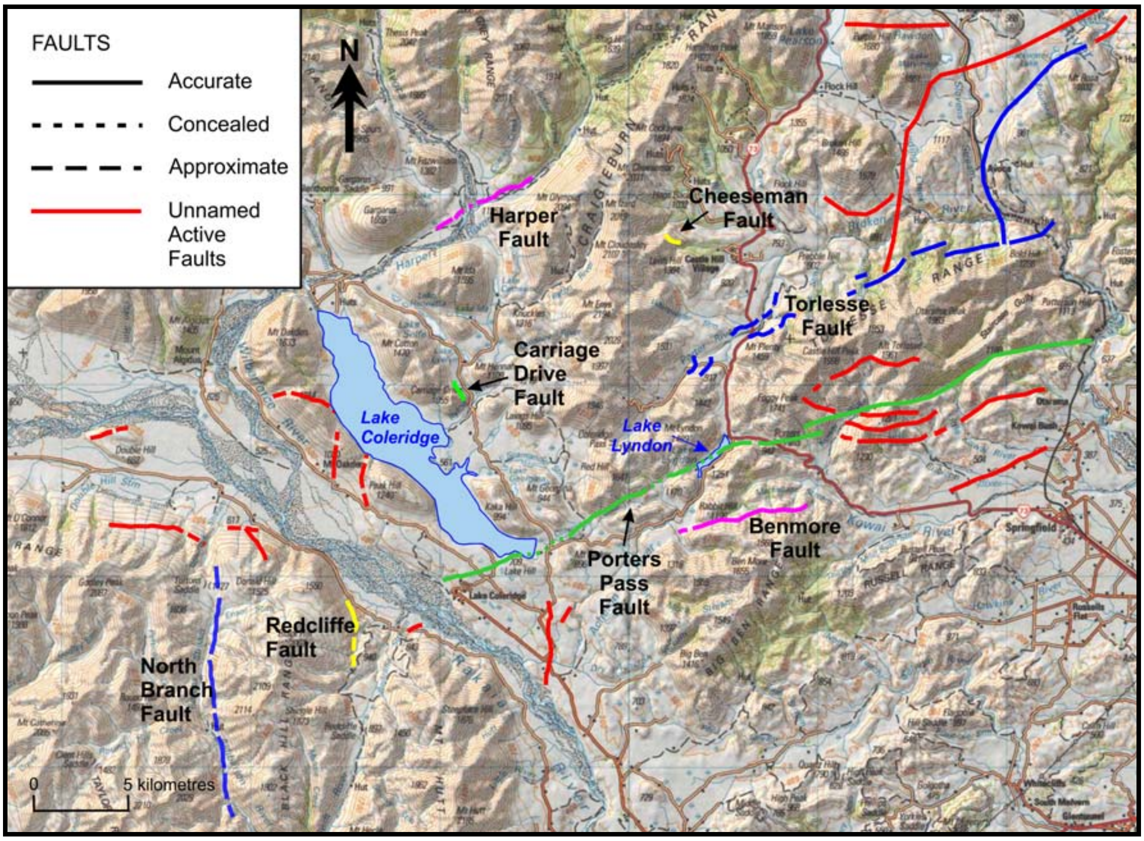

Figure 4.4: Local active faults within 15 km of Lakes Lyndon and Coleridge.

Table 4.1: Active faults within 15 km of Lakes Lyndon and Coleridge. Source: [a]Howard *et al.* (2005), [b]Pettinga *et al.* (2001), [c]Stirling *et al.* (2007), [d]Lee, (2004), [e]Stirling *et al.* (2002), [f]Elvy, (1999) and [g]Yetton & McCahon, (2006).

Fault	Fault Type	Recurrence Interval (years)	Recurrence Interval Class	Last Rupture (years ago)	Average Slip Rate (mm per year)	Single event Displacement (m)	Length (km)	Magnitude (M_w)
Harper	Reverse	>10,000[b]	V	>10,000[b]	-	-	49	7.1[b]
Cheeseman Fault Zone (Cheeseman and Craigeburn Faults)	Reverse	2200[c]	II	-	0.6[c]	3[e]	22	6.8[c]
Torlesse	Reverse	3000[c]	II	-	0.5[c]	-	51	7.2[c]
Carriage Drive	Reverse[g]	-	-	c.755 ± 35[d]	-	-	<1	-
Porters Pass	Oblique strike-slip	< 2000[a]	I	500-700[b]	2.7-5[b]	5.5-7[a]	40	7.4[c]
North Branch	Strike-slip	-	-	-	-	-	13	-
Redcliffe	Strike-slip	-	-	>10,000[f]	-	-	5	-
Benmore	-	-	-	10,000-25,000[g]	-	-	7	-
Kowai	-	-	-	> 25,000[g]	-	-	20?	-

4.3.1.1 Harper Fault

The Harper Fault is a north-east trending thrust fault, extending c. 49 km from the north-west end of Lake Coleridge to the Waimakariri River (Pettinga *et al.*, 1998; Yetton & McCahon, 2006). Pettinga *et al*. (2001) describe the fault as dipping to the south-east at approximately 20º to 50º. Mapping by Chamberlain (1996) revealed a 25 to 35 km east-facing, west-dipping thrust fault immediately adjacent to and west of the Harper Fault (Pettinga *et al.*, 1998). As paleoseismic data is not available for the Harper Fault or adjacent structures, slip rates and displacement values have not been established. It is inferred, however, that the last rupture event along the Harper Fault occurred more than 10,000 years ago (Pettinga *et al.*, 2001). However, the Harper Fault appears to have acted as the southern boundary to aftershocks following the Arthur's Pass earthquake in 1994 (Abercrombie *et al.*, 2000). No evidence of surface rupture was found (ibid). Due to this event, this fault should be considered as a potential earthquake source capable of producing M_w 7.1 events (Pettinga *et al.*, 2001). A seismically active portion of the Harper Fault is shown in Figure 4.4.

4.3.1.2 Cheeseman and Craigieburn Faults (Cheeseman Fault Zone)

The Cheeseman Fault Zone trends north-north-east along the eastern base of the Craigieburn Range. The fault zone consists of the Cheeseman and Craigieburn thrust faults and extends for approximately 22 km, dipping on average at 45º to the west (Pettinga *et al.*, 2001; Stirling *et al.*, 2007; Yetton & McCahon, 2006). Mapping carried out by Young (1997) revealed evidence for multiple rupturing events along both faults. Although evidence for Holocene earthquakes is ambiguous, displacement has occurred within glacial deposits, most probably belonging to the Poulter Advance, which retreated c.14,000 years ago (Pettinga *et al.*, 1998). The average displacement associated with each event has been estimated at c. 3 m, with an average slip rate of 0.6 mm per year (Stirling *et al.*, 2007; Stirling *et al.*, 2002). The most likely maximum magnitude that could be produced along this fault zone is 6.8, with a recurrence interval of about 2200 years (Stirling *et al.*, 2007).

4.3.1.3 Torlesse Fault

The Torlesse Fault extends c. 51 km in a north-east direction c. four km north of Lake Lyndon. It is believed to be a reverse fault, dipping 50º to 80º to the south-east (Pettinga *et al.*, 2001). A detailed paleoseismic study has not been undertaken for the Torlesse Fault and past events have, therefore, not been constrained. However, the fault is thought to be seismogenically active and is thought to have ruptured frequently throughout the late Quaternary (Pettinga *et al.*, 1998). A recurrence interval of 3000 years has been inferred with an average slip rate of 0.5 mm per year. The maximum magnitude of a future earthquake along this fault is c. M 7.2 (Stirling *et al.*, 2007).

4.3.1.4 Carriage Drive Fault

The Carriage Drive thrust fault trends north-north-west along the north-eastern flank of Carriage Drive, a hill situated on the eastern shores of Lake Coleridge. According to Lee (2004), this fault dips at c. 57º to the south-west. Radiocarbon dates obtained from within the fault scarp suggest two rupture events occurring at c. 4428 ± 35 years B.P. and 755 ± 46 years B.P. (ibid). However, Yetton and McCahon (2006) placed this fault in Activity Class II, which according to a fault classification system established by Pettinga *et al.* (1998), means that the fault is known to displace deposits of the late last glaciation (i.e. younger than 25,000 years old), but is not proven to displace Holocene deposits. This uncertainty, therefore, requires further research.

4.3.1.5 Porters Pass Fault

The Porters Pass Fault, c. 40 km long, trends east-north-east in the foothills of the Southern Alps between the Rakaia and Waimakariri Rivers. A trace of the fault can be seen lying within glacial deposits between the eastern side of the Rakaia River and the south-western side of Lake Coleridge, where it crosses beneath the penstocks of the Lake Coleridge Power Station. The western end of the Porters Pass Fault is then inferred to cross the southern tip of Lake Coleridge, extend through the Lyndon-Acheron Valley to Lake Lyndon, where it also crosses the lake’s southern end. There is a visible fault trace to the south-west of Lake Lyndon and also along the eastern side of the lake. There has been a reasonable amount of work conducted on the Porters Pass Fault in recent times, especially in regard to Holocene paleoearthquakes. Key findings of studies carried out by Howard (2001) and Howard *et al*. (2005) are now summarised.

The Porters Pass Fault is comprised of a series of discontinuous Holocene-active fault segments. The fault is predominantly a right-lateral strike-slip fault, but it also displays components of both normal and reverse oblique motion. This fault comprises the western end of the broader Porters Pass to Amberley Fault Zone (PPAFZ), an east-north-east trending zone of complexly interconnected, active faults, extending 100 km towards the town of Amberley and offshore (Cowan *et al.*, 1996; Pettinga *et al.*, 2001).

The Porters Pass Fault can be broadly divided into two segments based on behavioural properties. The western segment, c. 14 km long, extends from the Rakaia River and terminates just west of Red Lakes. Evidence for only one surface-rupturing earthquake has been found on this segment, which displaces 10,000 to 14,000 year old glacial deposits of the Acheron Advance. In contrast, at least six Holocene earthquakes are assumed to have occurred along the eastern segment of the fault (c. 32 km long)

(Howard *et al.*, 2005). No earthquakes have occurred along the fault in historical times (within the last 150 years).

The average strike of the Porters Pass Fault is 75˚, but because the fault is segmented, the strike varies between 58˚ to 98˚ (Howard *et al.*, 2005). The dip and dip direction of the fault also varies locally, due to topographic loading affecting the dip near the ground surface. As the fault crosses steep hill slopes, it tends to dip towards the topographic high and because the fault crosses range fronts sloping to both the north and south, the dip direction changes along the fault length. The amount of dip at the ground surface ranges mostly between 60˚ to 80˚ but is inferred to be vertical at depth (ibid).

At least six Holocene earthquakes have been identified on the eastern segment of the PPF. These events have been dated at 8400-9000, 5700-6700, 4500-6000, 2300-2500, 800-1100 and 500-600 years old (Howard *et al.*, 2005). Along the western segment, only one surface-rupturing earthquake has been identified. This event is thought to align with the 2300-2500 years BP event along the eastern segment, implying a possible rupture along the full length of the Porters Pass Fault (ibid). 7±2 m of strike slip movement has been identified along the western segment of the fault, displacing the Acheron glacial deposits. As all strike slip displacement along the fault is assumed to be coseismic, this data implies a Holocene slip rate of 0.3 to 0.9 mm per year along this segment. C. 33±4 m of strike slip displacement has been identified on the eastern segment, indicating a Holocene slip rate of c. 3.2 to 4.1 mm per year. Displacement per event along the whole of the Porters Pass Fault has been estimated at 5.5 to 7 m (Howard *et al.*, 2005). Rupture lengths can vary depending on whether just part of the Porters Pass Fault ruptures, such as the c. 32 km long eastern segment, or the whole length of the PPAFZ (c.100 km) ruptures.

The Porters Pass Fault is capable of generating large magnitude events ranging from M 7.1 to M 7.7. An earthquake generated along only part of the Porters Pass Fault, such as the eastern segment, is likely to produce a magnitude of around M 7.1 with an average displacement of 4 m. A rupture along the entire PPAFZ is capable of generating a magnitude 7.7 earthquake. An average displacement of 8 m would accompany such an event (Howard *et al.*, 2005). Accurate recurrence intervals along the Porters Pass Fault are uncertain due to the relatively short time span over which earthquake events have been identified. Therefore, any estimates must be treated with caution. In the case of the eastern segment, where six events have been identified within the last 9000 years, recurrence intervals can be calculated to range from 100 or 200 years to 3700 years, with an average recurrence interval of c. 1500 years. Recurrence intervals along the western segment are even more uncertain. As there is only evidence of one surface-rupturing event displacing Acheron glacial deposits along this segment, other ruptures, which may have occurred before the identified 2300 to 2500 year event, would most probably predate this glacial advance. Therefore, the recurrence interval must be at least c. 7500 to 11700 years (Howard *et al.*, 2005). To err on the side of caution, a recurrence interval for the PPF will be assumed as being <2000 years.

According to Howard *et al*. (2005), the elapsed time since the last event along the western side of the Porters Pass Fault is c. 2300 to 2500 years. Assuming the recurrence interval of c. 7500 to 11700 years, a rupture on this part of the fault is not expected for another c. 5000 to 9400 years. This rough calculation has, however, a lot of uncertainty associated with it. An earthquake along the eastern segment could trigger a rupturing event along this part of the fault at anytime. Elapsed time since the last event along the eastern segment of the Porters Pass Fault is estimated at c. 500 to 600 years (ibid). Therefore, taking into consideration a recurrence interval of somewhere between 1500 to 2000 years, this segment could stay inactive for another 1000 years or so. However, identified earthquakes on this segment have occurred as little as 100 to 200 years apart.

4.3.1.6 Benmore Fault

The Benmore fault is located to the south-east of Lakes Lyndon and Coleridge and strikes parallel to the Porters Pass Fault in an east-north-east direction. It is thought to be a relatively minor fault trace but has not been studied in any detail (Yetton & McCahon, 2006). According to Yetton and McCahon (2006), there is evidence for the Benmore Fault displacing deposits of the late last glaciation but no evidence for the fault displacing Holocene deposits.

4.3.1.7 North Branch and Redcliffe Faults

The North Branch and Redcliffe faults trend north-south on either side of the Black Hill Range. The North Branch Fault, which is located along the western flank of the range, is c. 13 km long and its seismic characteristics are unknown. The Redcliffe Fault extends for at least 5 km along the north-east face of range. Once again, a detailed investigation of this fault has not been undertaken. However, Elvy (1999) noted evidence for repeated rupture during the late Quaternary and termed the Redcliffe fault as active. Therefore, despite a lack of understanding of both faults, they must still be considered as possible seismic threats due to their close proximity to Lake Coleridge.

4.4 Active Faults in the Vicinity of Lake Tekapo

Lake Tekapo is situated within a region where deformation is dominated by oblique reverse and thrust faulting (Pettinga *et al.*, 2001). Historically, this region has displayed a low level of seismicity compared with other parts of New Zealand. Despite this, a number of significant active faults occur near Lake Tekapo, with the Alpine Fault being situated less than 60 km away. Therefore, the seismic threat to Lake Tekapo is significant.

4.4.1 Local Earthquake Sources

The closest major active faults to Lake Tekapo are the Forest Creek Faults, the Fox Peak Faults and the Irishman Creek Fault Zone (Figure 4.5). These faults are also capable of generating earthquakes with magnitudes M_w7 or greater. A number of other faults have been identified close to the lake but their seismic properties remain wholly unknown. Such faults include the Tekapo River Fault as proposed by Long *et al*. (2003). A summary of the known, named faults and their characteristics are provided in Table 4.2.

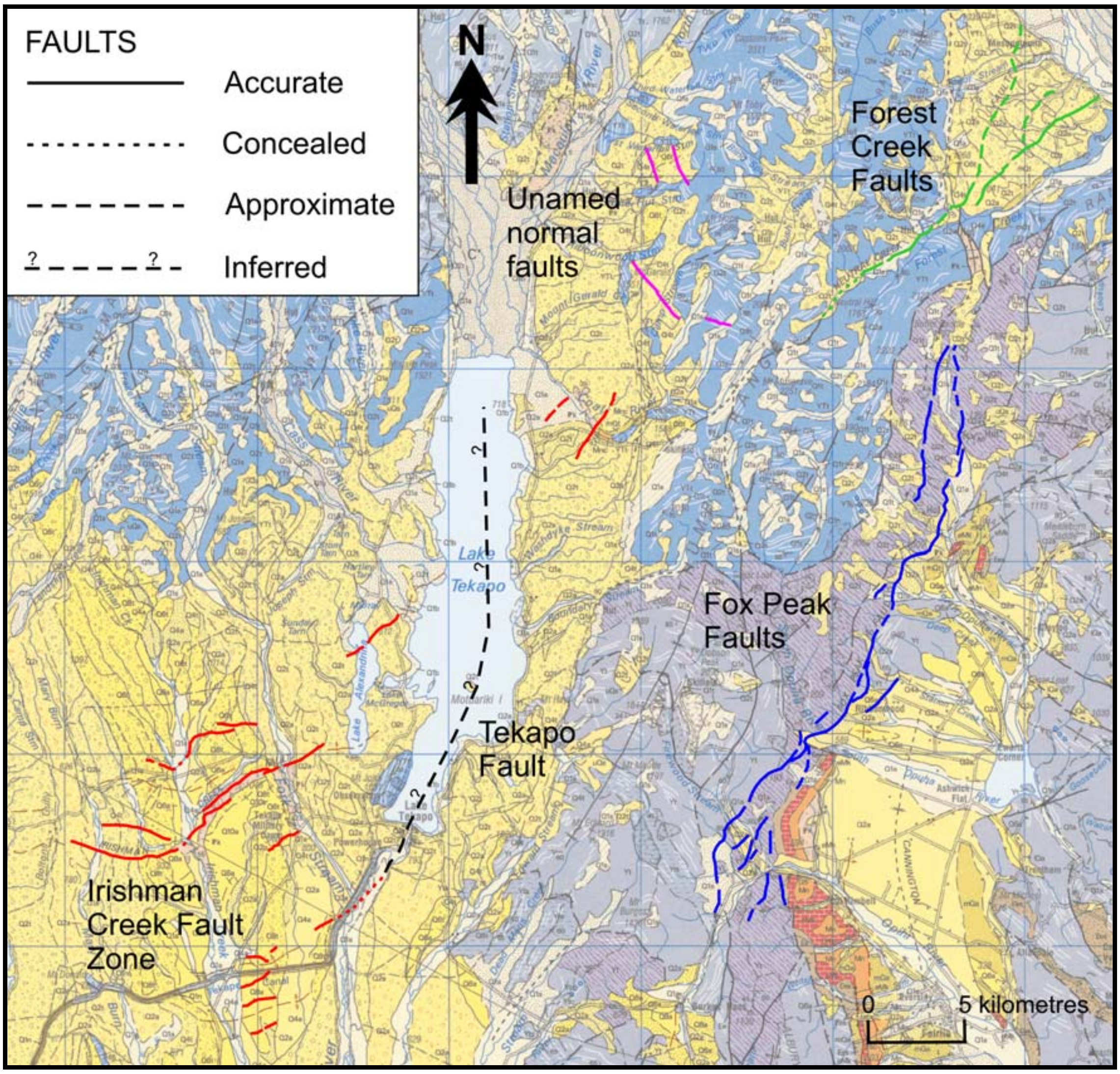

Figure 4.5: Local active faults within 15 km of Lake Tekapo.

Table 4.2: Active faults within 15 km of Lake Tekapo. Source: [a]Stirling *et al.* (2007), [b]Pettinga *et al.* (2001), [c]Upton *et al.* (2004) and [d]Stirling *et al*. (2002).

Fault	Fault Type	Recurrence Interval (years)	Recurrence Interval Class	Last Rupture (years ago)	Average Slip Rate (mm/year)	Single event Displacement (m)	Length (km)	Magnitude (M_w)
Irishman Creek Fault Zone	Reverse	4000[a]	III	-	0.6[a]	2-6[b]	40	7.1[a]
Tekapo River Fault	Reverse	-	-	-	-	-	-	-
Lake Heron - Forest Creek Faults	Reverse	3400[a]	II	-	0.9[a]	-	50	7.3[a]
Fox Peak Faults	Reverse	2000[a]	I	<2000?[c]	1.5[a]	4[d]	50	7.2[a]

4.4.1.1 The Irishman Creek Fault Zone

The Irishman Creek Fault Zone is made up of several parallel active fault traces, which trend north-east between Lakes Pukaki and Tekapo (Figure 4.5) (Pettinga *et al.*, 1998). The fault zone, which is approximately 15 km wide, consists of reverse faults and is inferred to extend into the middle of Lake Tekapo, possibly joining up with the Forest Creek Faults, or terminating against the inferred Tekapo River Fault (Upton & Osterberg, 2007). The main fault within the zone, the Irishman Creek Fault, is considered to be the dominant structural feature of the region and is responsible for the formation of the Old Man Range, which has a maximum relief of 150 m (Chetwin, 1998).

Recurrence intervals for the fault zone do not seem to be well constrained. However, according to weathering rind data carried out by McSaveney (1991), a recurrence interval of 1290±90 years has been estimated for major events along the Irishman Creek Fault within the past 5000 years. Stirling *et al.* (2007) stipulate a recurrence interval of c. 4000 years for the fault. Slip rates for the fault zone seem to be more consistent, with an average slip rate of c. 0.6 mm per year (Amos *et al.*, 2007; Chetwin, 1998; Stirling *et al.*, 2007). The fault zone is capable of producing earthquakes with a magnitude of approximately M_w 7 (Pettinga *et al.*, 2001; Stirling *et al.*, 2007).

4.4.1.2 The Tekapo River Fault

The Tekapo River fault is a north-south trending structure inferred to occur at depth in the vicinity of the Tekapo River (Long *et al.*, 2003). Deformation of glacial outwash surfaces in the region has been interpreted to represent the surface expression of the active, north-west dipping fault (ibid). According to Upton and Osterberg (2007), the fault does not appear to have been active within the last 16,000 to 20,000 years. However, the fault is thought to have had a prolonged history and is most likely to be reactivated (Long *et al.*, 2003). The Irishman Creek Faults and Forest Creek Faults are thought to terminate against the Tekapo River fault somewhere beneath Lake Tekapo (Upton & Osterberg, 2007).

4.4.1.3 The Forest Creek Faults

The Forest Creek Faults consist of a set of paired reverse faults, which trend north-east across the Two Thumb Range. The faults extend from the middle of Lake Tekapo to at least the Rangitata River (Upton *et al.*, 2004). The faults are partly responsible for the uplift of the Two Thumb Range, and have been clearly active in the late Cenozoic, thrusting older greywacke basement over Tertiary and younger rocks (ibid). Stirling *et al.* (2007) have grouped the Forest Creek faults along with the Lake Heron fault in their fault source parameter section. This group of faults has a recurrence interval of 3400 years, with an average slip rate of 0.9 mm per year. They are thought to be capable of producing M_w 7.3 earthquakes.

4.4.1.4 The Fox Peak Faults

The Fox Peak faults are a set of major reverse faults, trending north-north-east along the eastern side of the Two Thumb Range (Upton *et al.*, 2004). The faults extend for approximately 50 km, and along with the Forest Creek faults, have played an active role in uplifting the range (ibid). The average strike slip of the faults is 1.5 mm per year, with an average recurrence interval of 2000 years (Stirling *et al.*, 2007). This fault is also capable of producing relatively large earthquakes with magnitudes of c. M_w7.2 (ibid).

4.5 Other Major Earthquake Sources within 100 kilometres of Lakes Lyndon, Coleridge and Tekapo

Significant damage can also be produced by medium to large faults located up to 100 km from the lakes. There are a number of significant faults, which need to be considered, the most notable being the Alpine Fault. A summary of the main characteristics of each of these faults appears in Tables 4.3 and 4.4, and a more detailed summary of the Alpine Fault is also provided. It must also be noted that a lot more identified active faults exist within 100 km of the lakes, which are not included in the tables. This is because their seismic properties have not yet been established. No major offshore faults exist within 100 km of either lake and are therefore not considered in this study.

Table 4.3: Potential significant earthquake sources outside the immediate region (15 km) of Lakes Lyndon and Coleridge. Source: [a]Stirling *et al*. (2007), [b]Pettinga *et al*. (2001), [c]Stirling *et al*. (2002) and [d]Berryman & Villamor (2004).

Fault		Fault Type	Recurrence Interval (years)	Recurrence Interval Class	Last Rupture (years ago)	Average Slip Rate (mm per year)	Single event Displacement (m)	Length (km)	Magnitude (M_w)
Alpine	***Southern and central segments***	Oblique strike-slip	250[b]	I	291[b] (1717AD)	25[b]	8[b]	380	8.0[b]
	Northern Segment	Oblique strike-slip	500[b]	I	-	7.2[b]	5[b]	188	7.7[b]
Clarence (South-west)		Strike-slip	1500	I	-	3		75	7.4
Hope	***1888 rupture***	Strike-slip	200[c]	I		14[c]	1.5 – 2.6[b]	44	7.1[c]
	Conway	Strike-slip	300[c]	I		15[c]		81	7.4[c]
	Conway (offshore)	Strike-slip	1500[c]	I		5[c]		121	7.7[c]
	Taramakau	Strike-slip	600[c]	I		3[c]		30	6.9[c]
	Central-west	Strike-slip	100[c]	I		17[c]		36	7.0[c]
Kelly		Strike-slip	200	I		15		58	7.3
Kakapo		Strike-slip	400[c]	I	<10,000[b]	6.41[c]	-	47	7.1[c]
Browning Pass		Strike-slip	900	I		2		29	6.9
Poulter		Oblique strike-slip	2900[c]	II	79[d] (1929AD)	1[c]	-	48	7.1[c]
Kaiwara South		Reverse	4400	III		0.61		44	7.1
Omihi		Reverse	1000	I		1		17	6.6
Lowry		Reverse	2700	II		1		45	7.2
Waitohi		Reverse	4500	III		0.5		37	7.1
Esk		Oblique strike-slip	7500[c]	IV	-	.5[c]	-	40	7.0[c]
Lees Valley		Reverse	1600	I	-	1	1-3	26	6.9
Ashley		Reverse	5700	IV		0.55		52	7.3
Springbank		Reverse	7200	IV		0.22		26	6.8
Cust		Reverse	7400	IV		0.22		27	6.9
Hororata		Reverse	4800	III		0.5		40	7.1
Springfield		Reverse	5200	IV		0.5		43	7.2
Quartz Creek		Oblique strike-slip	5000	III		0.15		12	6.3
Mt Hutt-Mt Peel		Reverse	3900[c]	III	<10,000[b]	1[c]	2-4[b]	64	7.4[c]
Forest Creek Faults		Reverse	3400[a]	II	-	0.9[a]	-	50	7.3[a]
Fox Peak Faults		Reverse	2000[a]	I	<2000?[c]	1.5[a]	-	50	7.2[a]
Irishman Creek Fault Zone		Reverse	4000[a]	III	-	0.6[a]	2-6[b]	40	7.1[a]

Table 4.4: Potential significant earthquake sources outside the immediate region (15 km) of Lake Tekapo. Source: [a]Stirling *et al*. (2007), [b]Pettinga *et al*. (2001) and [c]Stirling *et al*. (2002).

Fault		Fault Type	Recurrence Interval (years)	Recurrence Interval Class	Last Rupture (years ago)	Average Slip Rate (mm per year)	Single event Displacement (m)	Length (km)	Magnitude (M_w)
Hororata		Reverse	4800[a]	III	-	0.5[a]	-	40	7.1[a]
Alpine	***Southern and central segments***	Oblique strike-slip	250[b]	I	291[b] (1717AD)	25[b]	8[b]	380	8.0[b]
	Northern Segment	Oblique strike-slip	500[b]	I	-	7.2[b]	5[b]	188	7.7[b]
Quartz Creek		Oblique strike-slip	5000[a]	III		0.15[a]	2.5[c]	12	6.3[a]
Mt Hutt-Mt Peel		Reverse	3900[c]	III	<10,000[b]	1[c]	2-4[b]	64	7.4[c]
Ostler		Reverse	3100[a]	II	500?[b]	1.35[a]	2-4[b]	68	7.4[a]
Ahuriri River		Reverse	5300[a]	IV	-	0.5[a]	2.5[c]	44	7.2[a]
Cardrona - north		Reverse	5200[a]	IV	-	0.4[a]	2[c]	34	7.1[a]
Blue Lake		Reverse	5300[a]	IV	-	0.47[a]	3[c]	41	7.2[a]
Albury		Reverse	12,100[a]	V	-	0.1[a]	-	20	6.7[a]
Brothers		Reverse	42,400[a]	VI	-	0.05[a]	-	35	7[a]
Dagelty		Reverse	7600[a]	IV	-	0.2[a]	3[c]	25	6.8[a]
Dryburgh		Reverse	36,400[a]	VI	>10,000[b]	0.05[a]	2.5[c]	30	6.9[a]
Stonewall		Reverse	24,200[a]	VI	-	0.05[a]	-	20	6.7[a]
Kirkliston		Reverse	5300[a]	IV	-	0.4[a]	3[c]	35	7[a]
Opawa		Reverse	36,400[a]	VI	-	0.05[a]	-	30	6.9[a]
Otemata		Reverse	51,500[a]	VI	-	0.02[a]	-	17	6.6[a]
Fern Gully		Sinistral	5400[a]	IV	-	0.6[a]	-	53	7.2[a]
Waitangi		Reverse	14,500[a]	V	<20,000[b]	0.15[a]	0.5-2.5[b]	36	7[a]

4.5.1 The Alpine Fault

The Alpine Fault, along with its northward continuation, the Wairau Fault, extends c. 650 km along the western side of the Southern Alps from Milford Sound to near Blenheim (Pettinga *et al.*, 1998). It is the most distinguishable expression of the Australian-Pacific plate boundary, linking the west-dipping subduction zone east of the North Island, to the east-dipping subduction zone southwest of Fiordland (Norris &

Cooper, 2000; Yetton *et al.*, 1998a). The Alpine Fault accommodates c. 70 to 75 per cent of the plate motion and is the most active fault in the South Island (Norris & Cooper, 2000). It lies approximately 65 km north-west of Lake Lyndon and 45 km north west of Lake Coleridge. As the fault is notable for repeatedly producing large earthquakes (on the order of magnitude 8), it represents one of the biggest seismic threats to the lake areas.

The Alpine Fault is a right-lateral strike-slip fault consisting of various segments, which behave differently (Aitken, 1999). The southernmost segment of the Alpine Fault dips very steeply and is completely strike-slip. The segments in the central region display slightly different characteristics due to the ongoing tectonic compression. These segments tend to dip at more moderate angles and have a significant dip-slip component. This section is known to be the most active part of the fault (Yetton *et al.*, 1998a). The northern segment, which starts from near the junction of the Alpine and Hope faults is predominantly strike-slip and appears to move at slower rates than the other segments. This is because movement is transferred to other faults in the Marlborough region, such as the Hope Fault (ibid). For the purpose of information in Tables 4.3 and 4.4, the southern and central segments of the Alpine Fault have been grouped together, as reflected in Pettinga *et al.* (2001) and Stirling *et al.* (2007).

The Alpine Fault has not ruptured in historic times (within the last 150 years) but is known to have ruptured at least four times within the last 900 years (Aitken, 1999). On average, each of these four earthquakes has produced 6 to 8 m of horizontal slip and 1 to 2 m of vertical movement (ibid). These four earthquakes are believed to have occurred in AD 1717, AD 1620, AD 1450 and AD 1220±50 years (ibid). Not all of these events ruptured along the entire fault. The rupture lengths of the 1717 and 1620 events were approximately 375 km and 200 km respectively. On this basis, these two latest earthquakes are believed to have been magnitude 8 events (ibid).

There is a large variance in recurrence intervals between inferred Alpine Fault events over the last 1500 years (Pettinga *et al.*, 2001). Time between events varies from 100 years to more than 380 years, giving an average recurrence interval of c. 250 years with a standard deviation of c. 96 years (ibid). As the last event occurred around 291 years ago, the threat of a large Alpine Fault event is imminent. According to Yetton *et al.* (1998a) the next Alpine Fault event will most likely have a magnitude of approximately 8, inflicting a number of serious consequences upon the South Island.

4.6 Historical Earthquakes in the Canterbury Region

The Canterbury region has experienced many earthquakes during historical times (since 1840). The location of earthquake epicentres since 1840 is illustrated in Figure 4.6. The majority of these historical ruptures have been relatively small events, unnoticed by the general population. Earthquakes in the region have also predominantly occurred at relatively shallow depths of less than 40 km. This reflects the continental collision behaviour, which characterises Canterbury. The historical record of smaller magnitude events must, however, be taken with caution. This is because the seismographs of the New Zealand National Network were not sufficient for recording events until 1943 (Pettinga *et al.*, 2001). The location and frequency of earthquakes up until this point relied heavily upon written accounts of felt effects. Therefore, a definitive list of earthquakes up until 1942 is incomplete (ibid). However, the more significant earthquakes with magnitudes of >7 affecting the Canterbury region have been identified with more confidence since the late 1840's.

Approximately 16 shallow earthquakes (at depths of <40 km) with magnitudes between 6 to 7.8 have occurred within or close to the Canterbury region since 1840 (Pettinga *et al.*, 1998). The location and size of these earthquakes are depicted in Figure 4.7. The majority of these large earthquakes occurred in the northwest area of Canterbury, with a number located in the vicinity of Lakes Lyndon and Coleridge. No significantly large earthquakes seem to have occurred around Lake Tekapo. However, if we take magnitude 5 events into consideration, it is clear that a few have occurred to the north of Tekapo (Figure 4.8). Significant events directly affecting each of the lake areas are discussed below.

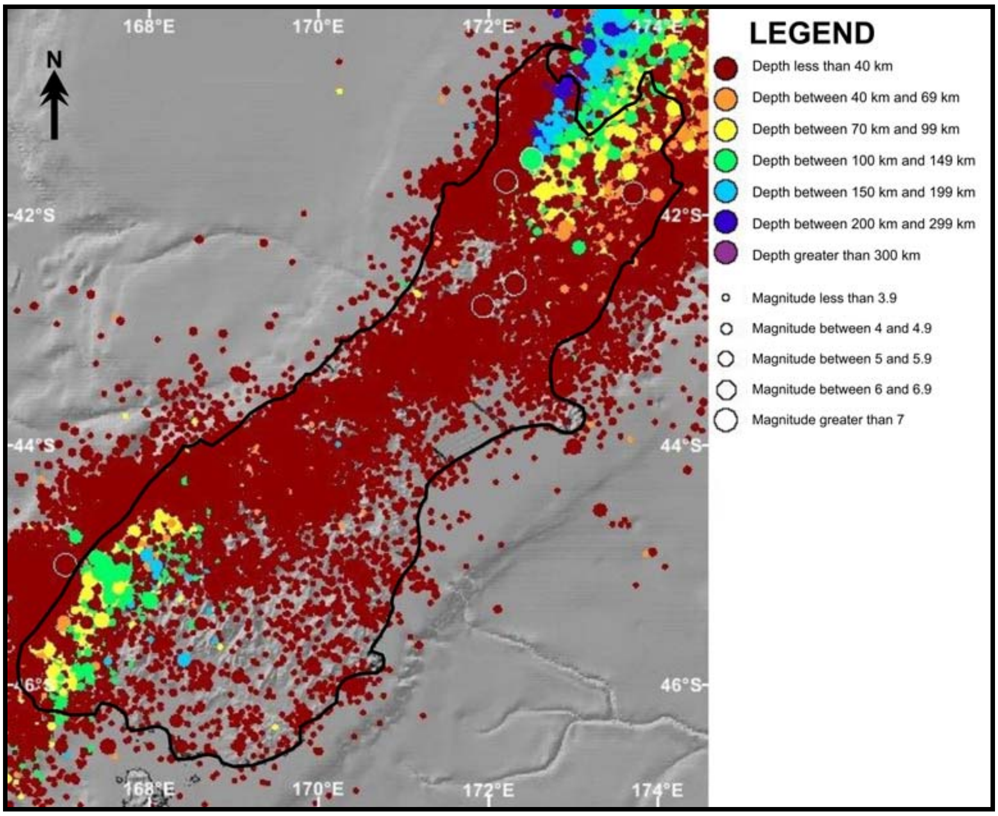

Figure 4.6: The epicentres of all known earthquakes within or close to the Canterbury region between 1840-2008. Modified from: www.geonet.org.nz

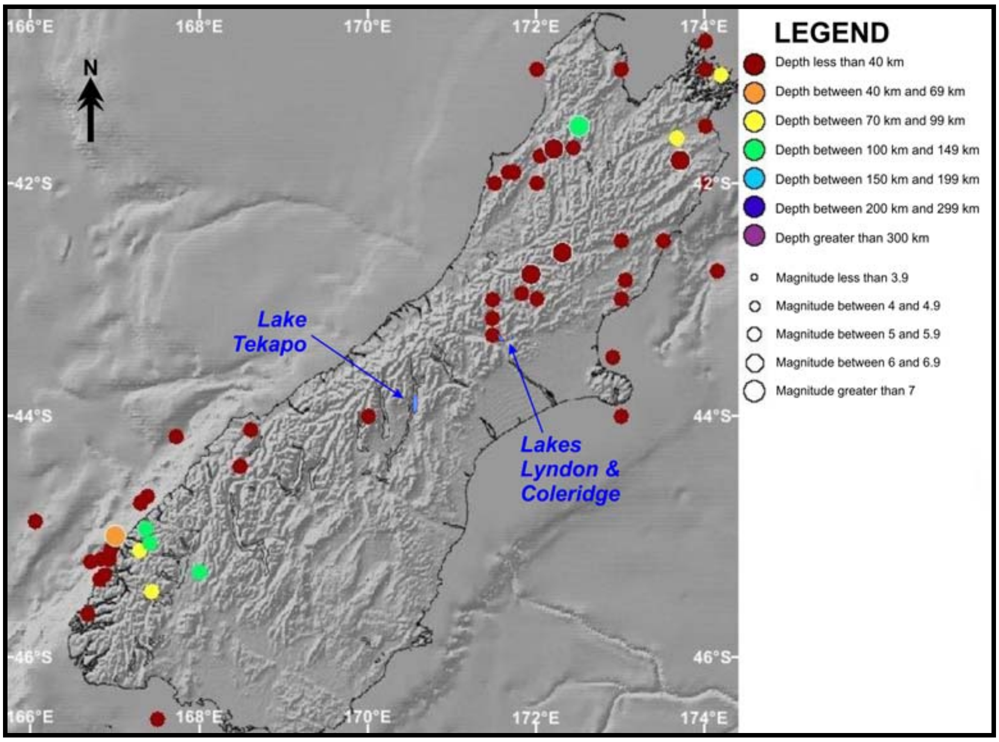

Figure 4.7: The location of earthquake epicentres within or close to Canterbury with magnitudes 6 or greater since 1840. Modified from: www.geonet.org.nz

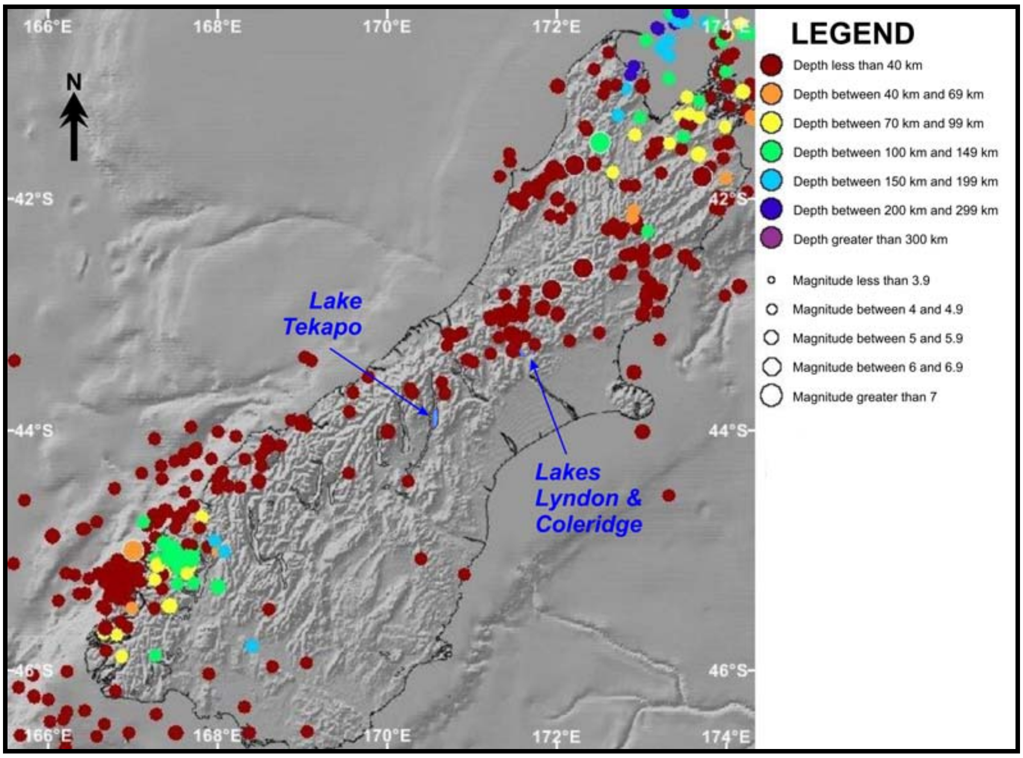

Figure 4.8: The location of earthquake epicentres within or close to Canterbury with magnitudes 5 or greater since 1840. Modified from: www.geonet.org.nz

4.6.1 Significant historical earthquakes around Lakes Lyndon and Coleridge

A number of significant earthquakes have been felt around Lakes Lyndon and Coleridge. For example, the 1929 Arthur's Pass and Murchison earthquakes, which registered magnitudes of c. 7.1 and 7.6 respectively, were felt strongly in the area (Britten, 2000; Cox & Barrell, 2007; Dowrick, 1994). No structural damage was reported, but shaking during the Murchison earthquake generated a c. 30 cm seiche in Lake Coleridge (Britten, 2000). The lake is reported to have remained cloudy for weeks following this event suggesting significant sediment disturbance within the lake (ibid).

A series of earthquakes, referred to as the Lake Coleridge Earthquakes, occurred around Lakes Lyndon and Coleridge during 1946 and these are the largest known events to have occurred near the lakes in historical times. The largest of the earthquakes occurred on June 26, 1946, and had a magnitude of approximately 6.2 (Pettinga *et al.*, 1998). This event was preceded by two foreshocks and followed by multiple aftershocks, which are thought to have extended until the end of 1949 (ibid). The largest aftershock had a magnitude of 5.8 (ibid). The epicentres of each of the earthquakes occurred within a circular region, about 35 km across, around Lake Coleridge (Figure 4.9) (Eiby, 1990). The epicentre of the largest event is thought to have been located near Mount Cheeseman in the Castle Hill basin (Yetton & McCahon, 2006). Modified Mercalli shaking intensities (Yetton *et al.*) of at least seven occurred around the lakes for about 50 km (Eiby, 1990). As a result of the earthquakes, minor structural damage occurred to buildings in the vicinity including the Lake Coleridge Power Station. It must be noted, however, that most of the buildings in the area were quite old and often unconventional in design. Extensive landslides also occurred as a result of the earthquakes, most notably in the area of maximum intensity (Eiby, 1990). For example, multiple landslides occurred around Mount Oakden, which is located on the northwest shores of Lake Coleridge.

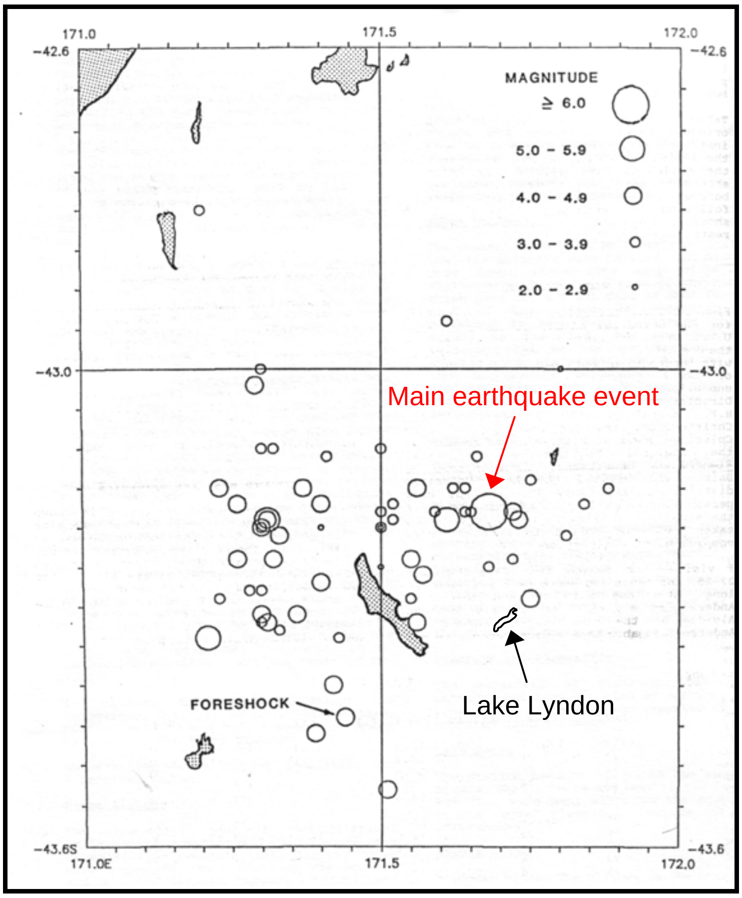

Figure 4.9: The epicentres of the Lake Coleridge earthquakes of 1946. Source: Modified from Eiby, (1990): 152.

Another earthquake, the June 18, 1994 M 6.7 Arthur's Pass earthquake, was also strongly felt across the region. The Coleridge Power Station once again sustained damage – multiple windows were broken and major cracks developed between the original building and its extension (Britten, 2000). A greater shaking intensity was felt at the northern end of the lake and as a result, slumping of canal banks occurred (ibid). Once again, there was significant sediment disturbance within the lake, which remained turbid for months (ibid).

4.6.2 Significant historical earthquakes around Lake Tekapo

The largest identified earthquake to have occurred near Lake Tekapo in historical times is the 1984 Godley earthquake. It is thought to have had a magnitude of somewhere between 5.9 to 6.1 and was felt from Westland to Christchurch (Bradshaw, 1984; Cox & Barrell, 2007; Doser *et al.*, 1999). Minor damage, such as the shattering of light fittings and broken windows, was recorded at Lilybank Station, just north of Lake Tekapo and at Franz Josef Hotel (Bradshaw, 1984). No active fault has been identified in the epicentral region but movement is thought to represent the southernmost extent of the Marlborough Fault System (Anderson *et al.*, 1993).

4.7 The Consequences of Earthquakes to the areas around Lakes Lyndon, Coleridge and Tekapo

There are a number of effects associated with earthquakes, including ground shaking, liquefaction, landslides, and tsunami and seiches, which can have potentially disastrous consequences to a region.

4.7.1 Ground Shaking

Ground shaking is the most widespread and prominent effect of earthquakes, having the potential to cause severe damage to lifelines and infrastructure. This is the result of seismic waves propagating through the earth from the release of energy at the epicentre of an earthquake (Yetton & McCahon, 2006). The severity of shaking within a particular area depends on a number of factors, including the earthquake magnitude, the distance from the earthquake epicentre and the local geological and geomorphological conditions (ibid). The level of shaking can be measured directly in terms of peak ground accelerations (PGAs), or indirectly by using the Modified Mercalli Intensity scale (MM scale) (Table 4.5) (Yetton *et al.*). The MM scale is a descriptive scale, which converts the intensity of shaking experienced by people, buildings and the natural environment into a scale of one to twelve. However, in New Zealand, the MM scale typically only goes up to MM 10, as this is the highest intensity observed in the country (Cox & Barrell, 2007; Hicks & Campbell, 1998).

In general, the severity of shaking will decrease with an increase in distance from the epicentre and with a decrease in the magnitude of an event. However, local site conditions, such as the geology or topography of an area, may amplify wave propagation resulting in the possibility of high levels of shaking from generally low intensity earthquakes. Areas underlain with large thicknesses of weak, unconsolidated sediments (>20 m) are susceptible to amplification of seismic waves during an earthquake (Cox & Barrell, 2007; Yetton & McCahon, 2006). Such areas include deltas, river plains, swamps and beneath estuaries (Cox & Barrell, 2007). The topography of an area also helps determine the ground shaking intensity, with a concentration of amplification occurring on ridges (Yetton & McCahon, 2006).

An updated probabilistic seismic hazard analysis was conducted for the Canterbury region by Stirling *et al.* (2007), with a series of new probabilistic seismic hazard maps produced. These maps depict the ground shaking intensities expected throughout Canterbury for return periods of 50, 150, 475 and 1000 years. The seismic hazard maps depicting ground shaking hazard intensities in terms of the MM scale are included (Figure 4.10). A site classification system, which is outlined in an article by McVerry et al. (2006) was taken into consideration while developing the probabilistic maps. Five subsoil classes are included in the classification system (A-strong rock, B-rock, C-shallow soil, D-deeper or soft soils and E-very soft soils). The hazard maps were created for uniform Class C (shallow soil) site conditions.

Table 4.5: The Modified Mercalli Intensity Scale. Source: Cox & Barrell, (2007):51.

MM 2	Felt by persons at rest, on upper floors or favourably placed.
MM 3	Felt indoors; hanging objects may swing, vibration similar to passing of light trucks.
MM 4	Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to passing of heavy traffic. Doors and windows rattle. Walls and frames of buildings may be heard to creak.
MM 5	Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Some glassware and crockery may be broken. Open doors may swing.
MM 6	Felt by all. People and animals alarmed. Many run outside. Objects fall from shelves. Glassware and crockery broken. Unstable furniture overturned. Slight damage to some types of buildings. A few cases of chimney damage. Loose material may be dislodged from sloping ground. A few very small (10^3m^3) soil and surface material landslides and rockfalls occur.
MM 7	General alarm. Furniture moves on smooth floors. Unreinforced stone and brick walls crack. Some pre-earthquake code buildings damaged. Roof tiles may be dislodged. Many domestic chimneys broken. Small falls of sand and gravel banks. Some fine cracks appear in sloping ground and ridge crests. Rockfalls from steep slopes and cuttings are common. A few small to moderate (10^3-10^5m^3) occur on steeper slopes, and there are instances of liquefaction at susceptible sites.
MM 8	Alarm may approach panic. Steering of cars greatly affected. Some serious damage to pre-earthquake code masonry buildings. Most reinforced domestic chimneys damaged, many brought down. Monuments and elevated tanks twisted or brought down. Some post-1980 brick veneer dwellings damaged. Houses not secured to foundations may move. Cracks appear on steep slopes and in wet ground. Significant landsliding in susceptible areas, with widespread small to moderate (10^3-10^5m^3) and some large slides. Collapse of roadside cuttings and unsupported excavations. Small sand fountains and other instances of liquefaction.
MM 9	Very poor quality unreinforced masonry destroyed. Pre-earthquake code masonry buildings heavily damaged, some collapsing. Damage or distortion to some pre-1980 buildings and bridges. Houses not secured to foundations shifted off. Brick veneers fall and expose framing. Conspicuous cracking of flat and sloping ground. General landsliding on steep slopes. Many small to large landslides (10^3-10^6m^3), and some very large ($>10^6m^3$) landslides and debris avalanches – forming dams and lakes in narrow valleys. Liquefaction effects intensified, with large sand fountains and extensive cracking or settlement of weak ground.
MM 10	Most unreinforced masonry structure destroyed. Many pre-earthquake code buildings destroyed. Many pre-1980 buildings and bridges seriously damaged. Many post-1980 buildings and bridges moderately damaged or permanently distorted. Widespread cracking of flat and sloping ground. Widespread and severe landsliding on sloping ground. Very large rock masses ($>10^6m^3$) displaced on steep mountain faces and coastal cliffs. Widespread and severe liquefaction.

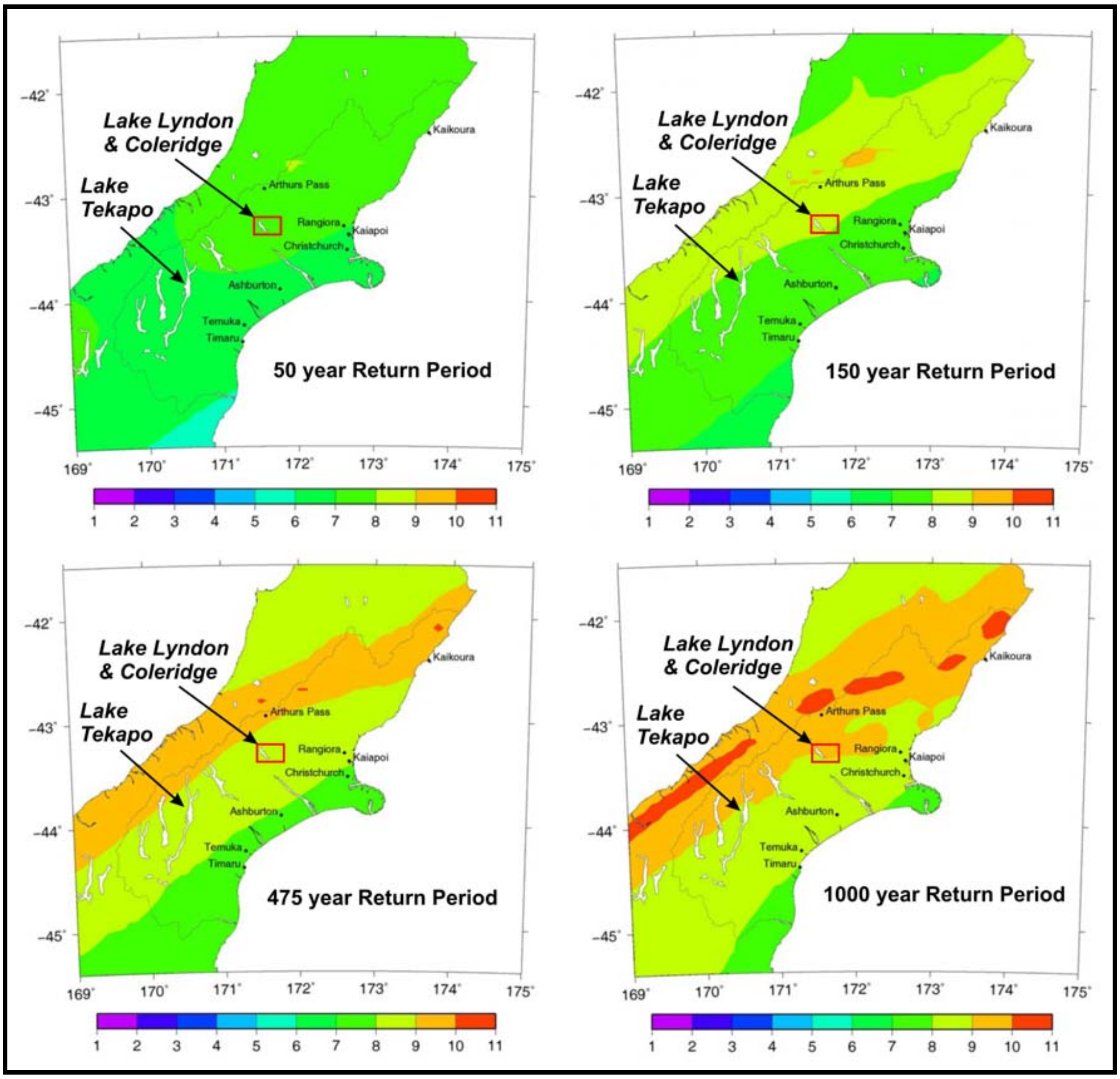

Figure 4.10: Modified Mercalli ground shaking intensities expected throughout the Canterbury Region for return periods of 50, 150, 475 and 1000 years on Class C (shallow soil) site conditions of McVerry *et al.* (2006). Modified from Stirling *et al.*, (2007).

The maps (Figure 4.10) discern that Class C site conditions around Lakes Lyndon and Coleridge will experience shaking intensities of MM 7 within a 50 year period. The shaking intensities will most likely increase to MM 8 for 150 and 475 year return periods and will reach a maximum intensity of MM 9 for a 1000 year return period. Intensities around Lake Tekapo will be approximately one MM unit less than Lakes Lyndon and Coleridge. A summary of these findings is provided in Table 4.6.

Table 4.6: The likely MM values for Class C (shallow soil) site conditions around Lakes Lyndon, Coleridge and Tekapo.

Return Period	Lake Lyndon	Lake Coleridge	Lake Tekapo
50	7	7	6
150	8	8	7
475	8	8	8
1000	9	9	8/9

However, these maps must be taken with caution, as a large variation from Class C site conditions can occur within most areas. Topographic amplification, which was not considered in the creation of the hazard maps, should also be considered. Areas which are susceptible to higher intensities of shaking than those defined by the probabilistic maps, should therefore be identified for each of the lake areas. In order to identify these more susceptible areas, the site conditions of the area need to be well constrained. Due to the time restrictions of this study, a detailed site investigation for each of the lake areas has not been possible. Therefore, information is taken from geological maps and previous studies.

The New Zealand site class definitions defined in McVerry *et al.* (2006) have been simplified by Yetton and McCahon (2006). They have condensed the five different classes into three broad zones, defined on the basis of geological assemblages. These three zones, which are used for the purposes of this study are summarised in Table 4.7.

Table 4.7: Ground Shaking Zones. Modified from Yetton and McCahon, (2006): 62.

Zone	**1 - Soft Soils**	**2 - Intermediate Ground Conditions**	**3 - Rock**
Geology	• Soft soils more than 20m deep. • Moderate density. • Recent alluvium or Holocene age.	• Weak or soft rock with soil cover. For example, soft tertiary rocks and old, well consolidated glacial moraine and outwash gravel. • Firm, deeper soils.	• Strong hard rock at shallow depth, such as greywacke.
Site Subsoil Class (McVerry *et al.*, 2006)	D or E	C, some B	A, some B

4.7.1.1 Ground Shaking Hazard of Lakes Lyndon and Coleridge

Based on the geological assemblages, which surround Lakes Lyndon and Coleridge, Figure 4.11 depicts the areas most likely to experience an increase or decrease in shaking intensities compared with what the probabilistic hazard maps by Stirling *et al*. (2007) suggest. Areas underlain with recent or Holocene-age alluvium, such as the river fan areas and the eastern side along Lake Lyndon, will most likely experience the greatest levels of shaking. However, these maps do not consider topographic amplification of seismic waves. Therefore, the ridges of the 'rock' (yellow) areas may experience shaking intensities similar to those of the 'soft soil' (red) areas. Expected shaking intensities for the different ground shaking zones around each of the lakes are summed up in Table 4.8.

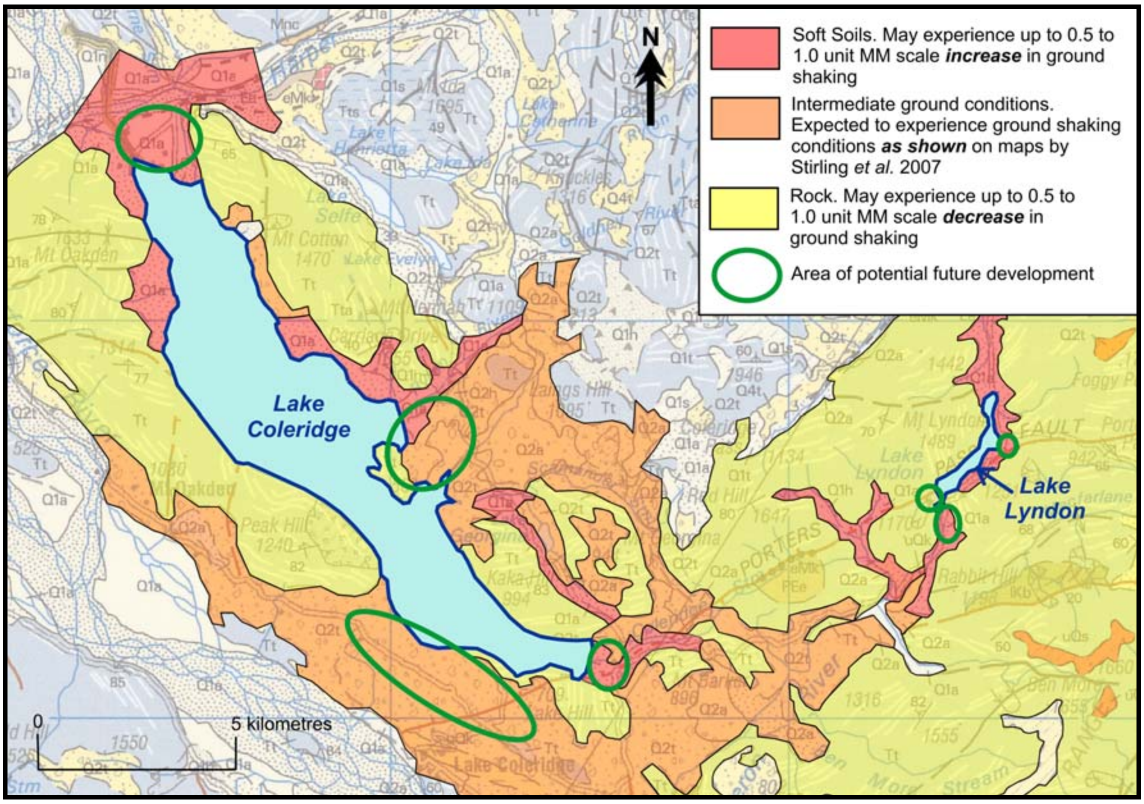

Figure 4.11: Ground shaking zones and areas of potential future development around Lakes Lyndon and Coleridge.

Table 4.8: Expected MM shaking intensities within ground shaking zones around Lakes Lyndon and Coleridge.

Return Period	'Red' Soft Soil Areas	'Orange' Intermediate Ground Conditions	'Yellow' Rock Areas
50	7.5-8	7	6-6.5
150	8.5-9	8	7-7.5
475	8.5-9	8	7-7.5
1000	9.5-10	9	8-8.5

4.7.1.2 Ground Shaking Hazard of Lake Tekapo

Based on the geological assemblages, which surround Lake Tekapo, Figure 4.12 depicts the areas most likely to experience an increase or decrease in shaking intensities than what the probabilistic hazard maps by Stirling *et al*. (2007) suggest. Areas underlain with recent or Holocene-age alluvium, such as the river mouth areas, will most likely experience the greatest levels of shaking. However, these maps do not consider topographic amplification of seismic waves. Therefore once again, the ridges of the 'rock' (yellow) areas may experience shaking intensities similar to those of the 'soft soil' (red) areas. Expected shaking intensities for the different ground shaking zones around the lake are summed up in Table 4.9.

Table 4.9: Expected MM shaking intensities within ground shaking zones around Lake Tekapo.

Return Period	'Red' Soft Soil Areas	'Orange' Intermediate Ground Conditions	'Yellow' Rock Areas
50	6.5-7	6	5-5.5
150	7.5-8	7	6-6.5
475	8.5-9	8	7-7.5
1000	8.5-10	8/9	7-8.5

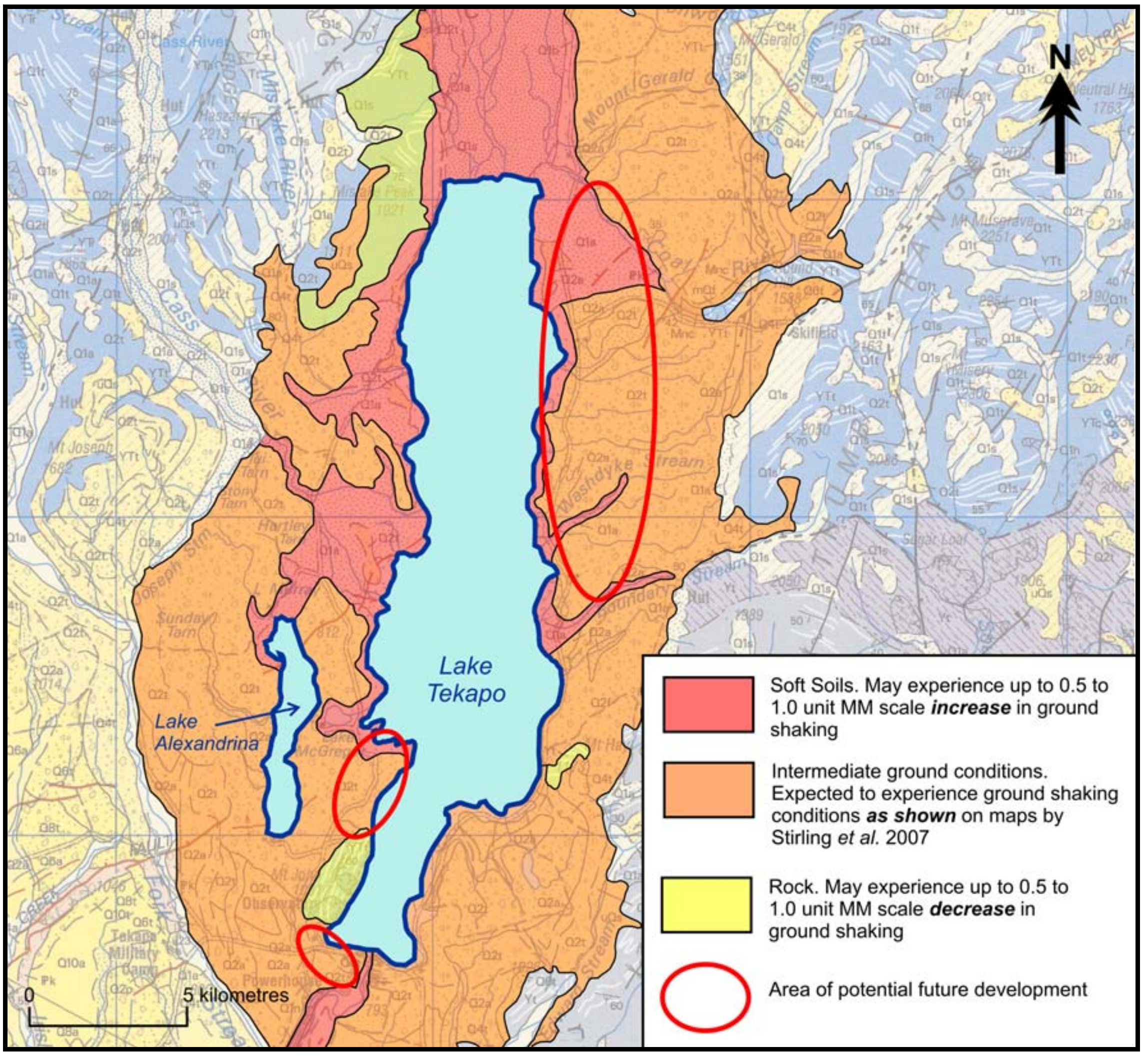

Figure 4.12: Ground shaking zones and areas of potential future development around Lake Tekapo.

4.7.2 Liquefaction

Liquefaction is another consequence associated with earthquakes, and commonly occurs as a result of ground shaking. It is the process in which water-saturated sands, silts and other loosely compacted soils temporarily loose their strength and behave like a fluid (Steinbrugge, 1982). As a result, damage can occur from landslides on moderate slopes, from foundations failing and sinking, and from flotation of buried structures (Benn, 1992; Yetton *et al.*, 1998a).

Loose, unsaturated, granular sediments, compact when strong shaking occurs (Yetton & McCahon, 2006). However, in saturated sediment, compaction is prevented as any voids are filled with water. Therefore, as shaking is sustained, the pore water pressure increases, which decreases the friction between sediment grains and causes the sediment to loose its strength (ibid). This process usually affects geologically young sediments, which are generally less than 10,000 years old (Benn, 1992). This is because consolidation and cementation usually takes place in sediments older than this (Yetton & McCahon, 2006). More specifically, the sediments most likely to liquefy are saturated, relatively uniform fine sands and loose, coarse silts (ibid). Other factors also strongly influence whether or not these sediments will liquefy. Liquefaction generally only occurs within sediments that are within 10 to 15 m of the ground surface, and where the water table is within 5 m of the surface (ibid). For example, saturated sediments close to river or lake levels are at risk of liquefying during an earthquake event. As part of the earthquake hazard assessment of the Selwyn District (Yetton & McCahon, 2006), a section was devoted to the liquefaction potential. Information regarding Lakes Lyndon and Coleridge will be drawn from here.

4.7.2.1 Liquefaction Susceptibility around Lake Lyndon

The area immediately to the north, east and south-east of Lake Lyndon is composed of Holocene alluvium (Cox & Barrell, 2007). There is, therefore, a low potential for liquefaction to occur (Figure 4.13). The reset of the land around the lake is composed of Torlesse Supergroup rocks and, therefore, has a nil to extremely low potential for liquefaction.

4.7.2.2 Liquefaction Susceptibility around Lake Coleridge

The majority of deposits surrounding Lake Coleridge are very low risk with respect to liquefaction potential (Figure 4.13). The slopes surrounding the lake are predominantly Torlesse greywacke and moraine deposits, which are generally consolidated and have a very low or nil water content. There are a few places, however, which must be considered as areas of possible local liquefaction. This includes the Harper Fan and areas immediately adjacent to the Ryton River and Coleridge Stream.

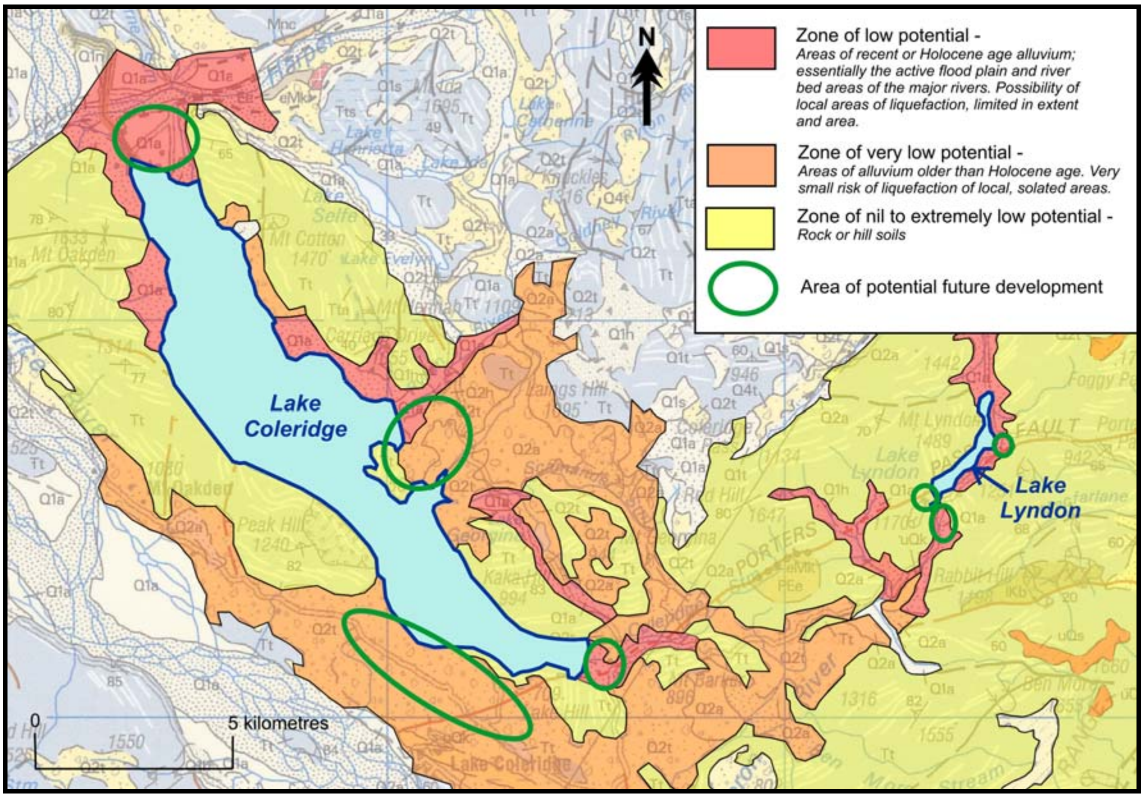

Figure 4.13: Liquefaction susceptibility zones around Lakes Lyndon and Coleridge.

These deposits consist of recent or Holocene alluvial gravels. According to Yetton and McCahon (2006), this type of deposit represents a zone of low potential, and any liquefiable areas are likely to be relatively small. However, the study carried out by Yetton and McCahon was on a regional scale and as future development in the Ryton Bay and Harper Fan is most likely, more specific subsurface investigations of these areas should be undertaken in order to determine soil size grading, density, and depth to the water table (Yetton *et al.*, 1998a).

4.7.2.3 Liquefaction Susceptibility around Lake Tekapo

Lake Tekapo is primarily surrounded by moraine deposits, which Yetton *et al.* (1998a) determined as being unlikely sites for liquefaction. However, there are a few sites of potential liquefaction. These sites run adjacent to the major rivers draining into and out of the lake (Figure 4.14). These river plain deposits most likely contain a high water content and as they are very close in elevation to the river and lake water levels, liquefaction could occur.

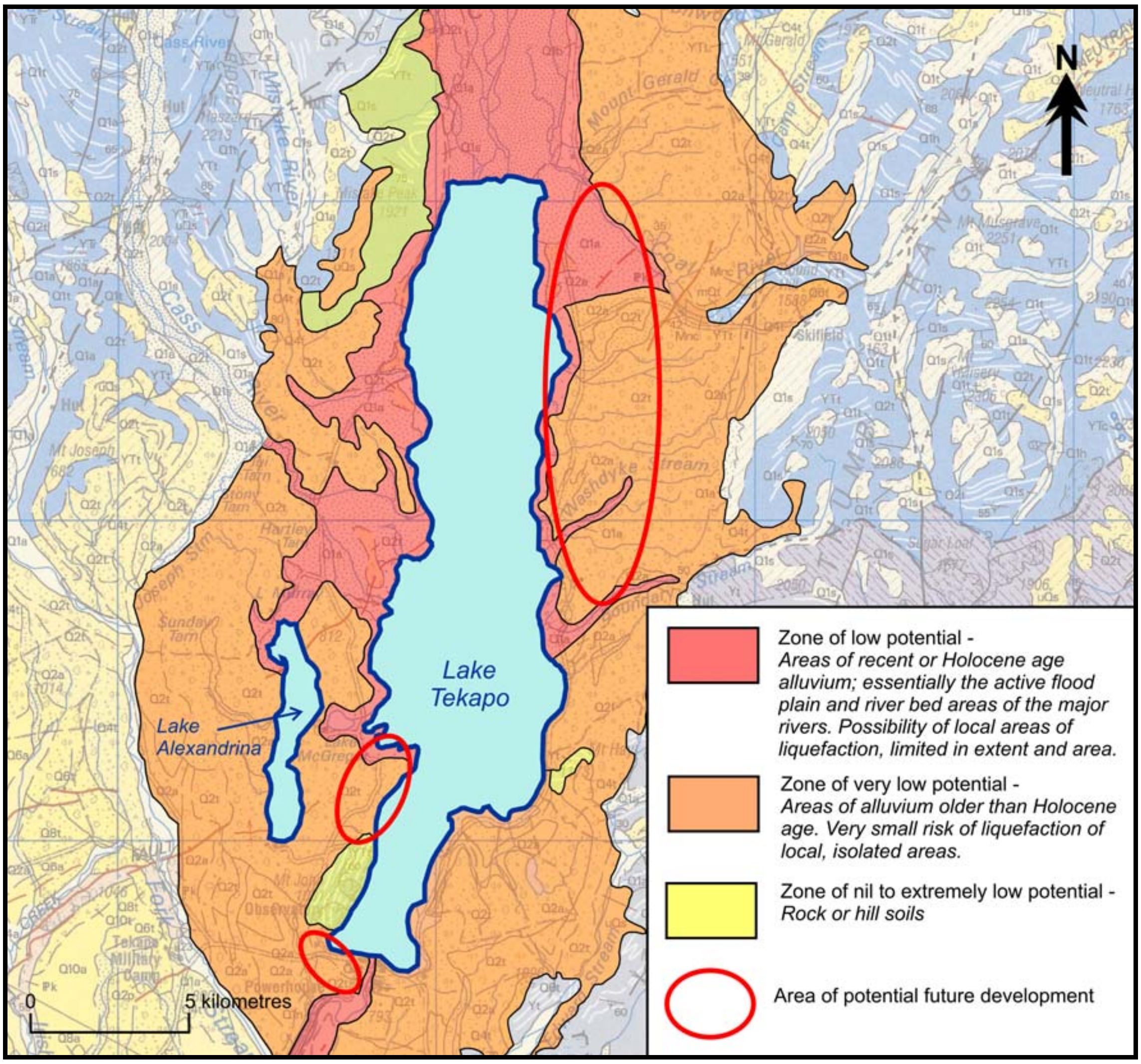

Figure 4.14: Liquefaction susceptibility zones around Lake Tekapo.

4.7.3 Landslides

Severe ground shaking during an earthquake also commonly induces landslides in hilly or mountainous terrane. As each of the lake areas are surrounded by such terrane, this is of particular concern. Landslide hazards to the lake areas are considered in Chapter 5.

4.7.4 Tsunami and Seiches

A well-known consequence often associated with seismic activity is the generation of tsunami, a series of very large waves, which can devastate coastal areas (Hicks &

Campbell, 1998). These large waves are generated by sudden, violent underwater disturbances, such as earthquake activity and landslides. Tsunami are by no means restricted to the open ocean but can also occur in bays, fjords, inland seas and lakes (Bryant, 2001).

Tsunami, seismic activity and landslides can also induce water within a lake to oscillate back and forth. These oscillations are known as seiches. This type of wave is also commonly produced by wind, and is often present on lakes. The water tends to oscillate at a particular frequency, which is controlled by the length and depth of the lake (Yetton *et al.*, 1998a). If this natural frequency matches that of earthquake waves, the water will begin to oscillate (if not already) and the waves will intensify (Eiby, 1989). Tsunami and seiche waves can reach heights of tens of metres (Hawley, 1984). They, therefore, present a very real danger to settlements near the shorelines of lakes, especially those within seismically active regions.

A seiche or tsunami event occurred on Lake Rotoroa following the 1929 M_s 7.8 Murchison earthquake. Benn (1992) recorded an extract from an article printed in the Greymouth Evening Star on the 20th of June, 1929.

> *"Lake Rotoroa rocked from side to side like a huge basin of water being tipped out. Half an hour after the main shake, the water receded from the hotel shore and exposed the lake bed for 50 yards. It then came back in a series of large waves. The bridge over the Gowan River at the lake was torn from its piles and banks of the river and was hurled upstream. The wrecked structure was carried still further upstream by the Gowan waters, which were temporarily flowing back into the lake. The water then returned back to its normal course."*

A disturbance was also observed in Lake Brunner following the 1929 earthquake and was reported to have *"sank down in the middle then come up like a typhoon"* (Benn, 1992).

A more extreme example of a tsunami in a relatively small body of water occurred in Lituya Bay on 9 July 1958. Lituya Bay is a glacially carved valley on the coast of Alaska and is notorious for having had a number of landslide-induced mega waves. The elongated bay is surrounded on three sides by steep mountainsides and glaciers. The bay is approximately 11.3 km long, 3 km wide and has a maximum depth of 220 m (Bryant, 2001). On July 9 1958, an earthquake measuring between M_s 7.9 to 8.3 occurred about 20 km from the head of the bay (ibid). The fault had a strike-slip component of 6.3 m and a dip-slip component of 1.1 m (ibid). The earthquake triggered a landslide containing c. 30 x $10^6 m^3$ of material to enter the head of the bay (Bryant, 2001; Wieczorek *et al.*, 2007). As it entered the water, it produced a wall of water that rose about 524 m above sea level (Bryant, 2001). This surge consumed the opposite shore and sent a 30 to 50 m high tsunami down the bay, claiming at least two lives (ibid). Once the tsunami left the bay, it dissipated very quickly. Although this example is an extreme event, it demonstrates how landslides entering into a semi-enclosed or fully closed body of water can produce extremely large and damaging waves.

For a fault rupture to directly cause a tsunami, a vertical component of slip must have occurred beneath the body of water (Hicks & Campbell, 1998). It also takes a reasonably big (at least a magnitude 7 event) and shallow earthquake (<70 km) to generate a tsunami (ibid). However, tsunami have been generated by magnitude 5 events in the past (ibid). In the case of the lake areas, the biggest threat of tsunami or seiche development would come from seismically-induced landslides entering the lakes. This type of event has been known to produce significant waves and as steep slopes enclose or partially enclose each of lakes Lyndon, Coleridge and Tekapo, this is of some concern. The threat of landslide-induced tsunami is also dealt with in Chapter 5.

4.8 Chapter Summary

- The earthquake hazard and risk assessments carried out for the Canterbury Region imply that a significant seismic threat exists. Consequences to the lake areas could occur from low to moderate magnitude events from near-field faults (within 15 km of the lakes) or from medium to large faults located up to 100 km from the lakes.

- A large number of active faults has been identified in the Lakes Lyndon and Coleridge area. Most faults in this region have, however, not been studied in-depth and their seismic properties remain unknown. The most serious threat comes from the Porters Pass Fault, which crosses through both lakes. Work carried out on this fault, along with other faults in the region, indicate that most of them are capable of producing M7 or greater earthquakes. A number of significant faults also occur within 15 km of Lake Tekapo and these are also capable of producing M7 earthquakes. The greatest threat from a more distant fault to each of the lakes in this study comes from the Alpine Fault.

- There are a number of effects associated with earthquakes, including ground shaking, liquefaction, landslides, and tsunami and seiches, which can have potentially disastrous consequences to a region. Landslide hazards are dealt with in Chapter 5. Ground shaking is the most widespread and prominent effect of earthquakes, and has the potential to cause severe damage to lifelines and infrastructure. The severity of shaking depends on earthquake properties and local site conditions. For example, deltas and river plains will potentially experience a greater intensity of shaking compared to areas with more consolidated deposits. A new series of probabilistic seismic hazard maps were produced by Stirling *et al*. in 2007, which depict the ground shaking intensities expected throughout Canterbury for given return periods. Lakes Lyndon and Coleridge can expect to experience shaking intensities between 7 to 9 for return periods of between 50 and 1000 years and Lake Tekapo will generally experience one MM unit less intensity for the same return periods.

- Liquefaction is another consequence associated with earthquakes, and commonly occurs as a result of ground shaking. There is not a huge threat to the lakes areas, but there are areas around the lakes, which are more prone than others. The areas most prone to liquefaction around Lake Lyndon include the northern, eastern and south-eastern sides of the lake, which are composed of Holocene alluvium. Areas around Lake Coleridge, which may be at risk from possible local liquefaction, include the areas immediately adjacent to the Ryton River and Coleridge Stream and also the fan of the Harper River, which impounds the northern end of the lake. The deposits around the major rivers of Lake Tekapo may also experience local liquefaction effects.

- Another consequence associated with earthquakes is the generation of tsunami, which can travel at huge speeds and can devastate coastal areas. These large waves are generated by sudden, violent underwater disturbances, such as earthquake activity and landslides. Another type of wave, known as seiches, is also commonly produced during earthquake shaking and can reach heights of tens of metres. Tsunami and seiches, therefore, represent a very real danger to settlements near the shorelines of lakes.

CHAPTER 5 -
LANDSLIDE HAZARDS

5.1 Introduction

Landslides are common in the hill and mountain terrain that dominates the landscape around the Canterbury Lakes. Despite this, landslides have caused few deaths in the area, mostly due to there being few settlements in the mountainous terrain. However, as New Zealand's population grows and spreads, the risk from landslides to both people and property increases and this is of concern. Development in Canterbury, especially around the lake areas, is likely to encroach more and more on, or close to, steeper and less stable areas. It is, therefore, imperative that areas with a significant landslide risk are identified before development occurs, so that these areas can remain either undeveloped, or where practical, developed so that the landslide risk is kept to an acceptable level (Saunders & Glassey, 2007). Areas that have already been developed also need to be assessed for their landslide risk so that, where necessary, action can be taken to reduce the risk. This chapter introduces basic concepts of landslides, summarises past significant events around Lakes Lyndon, Coleridge and Tekapo and identifies areas around the lakes, which may be susceptible to future slope instability.

5.2 Understanding Landslides

The term 'landslide' describes "the movement of a mass of rock, debris or earth down a slope" (Cruden, 1991). There are many different kinds of landslides, all of which vary in shape, size and speed, ranging from singular rocks falling, to catastrophic failures of whole mountainsides. Figure 5.1 depicts an idealised landslide with commonly used terminology describing its features.

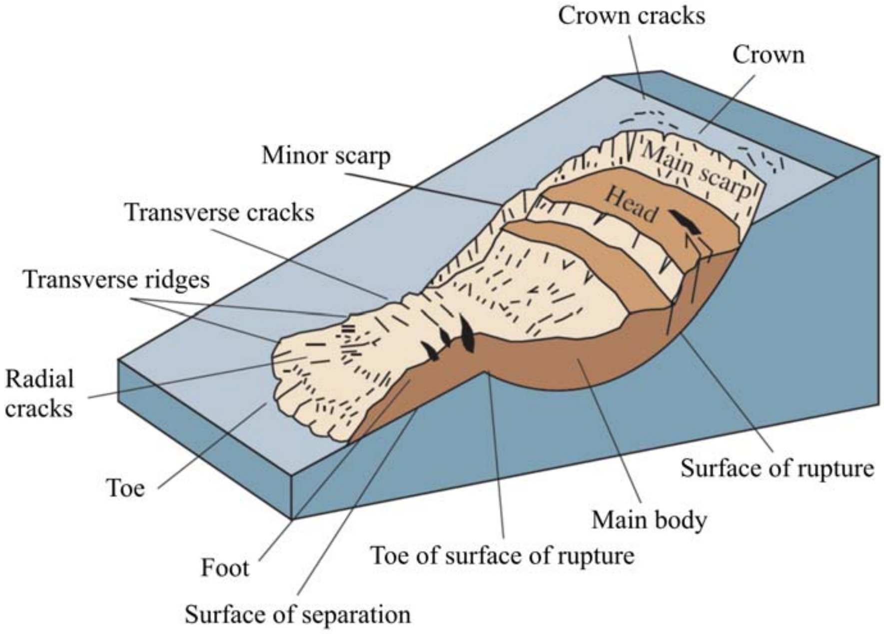

Figure 5.1: An idealised landslide with commonly used terminology for describing its features. Source: Highland, (2004).

5.2.1 Landslide Classification

There are many different landslide classification schemes, which vary slightly in their terminology and definitions. One of the most widely used schemes in New Zealand is that of Varnes (1978). In this scheme, landslides are classified on the basis of their type of movement and by the type of material involved (Table 5.1). There are five primary types of movement – falls, topples, slides, spreads and flows. A sixth group has been established to include combinations of two or more different types of movement. The types of material involved are classified as either rock or engineering soil, with soil further divided into coarse (debris) or fine (Yetton *et al.*) material. Diagrams of some of these different landslides are provided in Figure 5.2.

Table 5.1: Landslide Classification Scheme of Varnes (1978).

Type of Movement			**Type of Material**		
			Bedrock	**Engineering Soils**	
				Coarse	**Fine**
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	**Rotational**	**Few Units**	Rock slump	Debris slump	Earth slump
	Translational		Rock block slide	Debris block slide	Earth block slide
		Many Units	Rock slide	Rock slide	Rock slide
Lateral Spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow	Debris flow	Earth flow
Complex			Combination of two or more principal types of movement e.g. rock and debris avalanches (fall, slide and flow).		

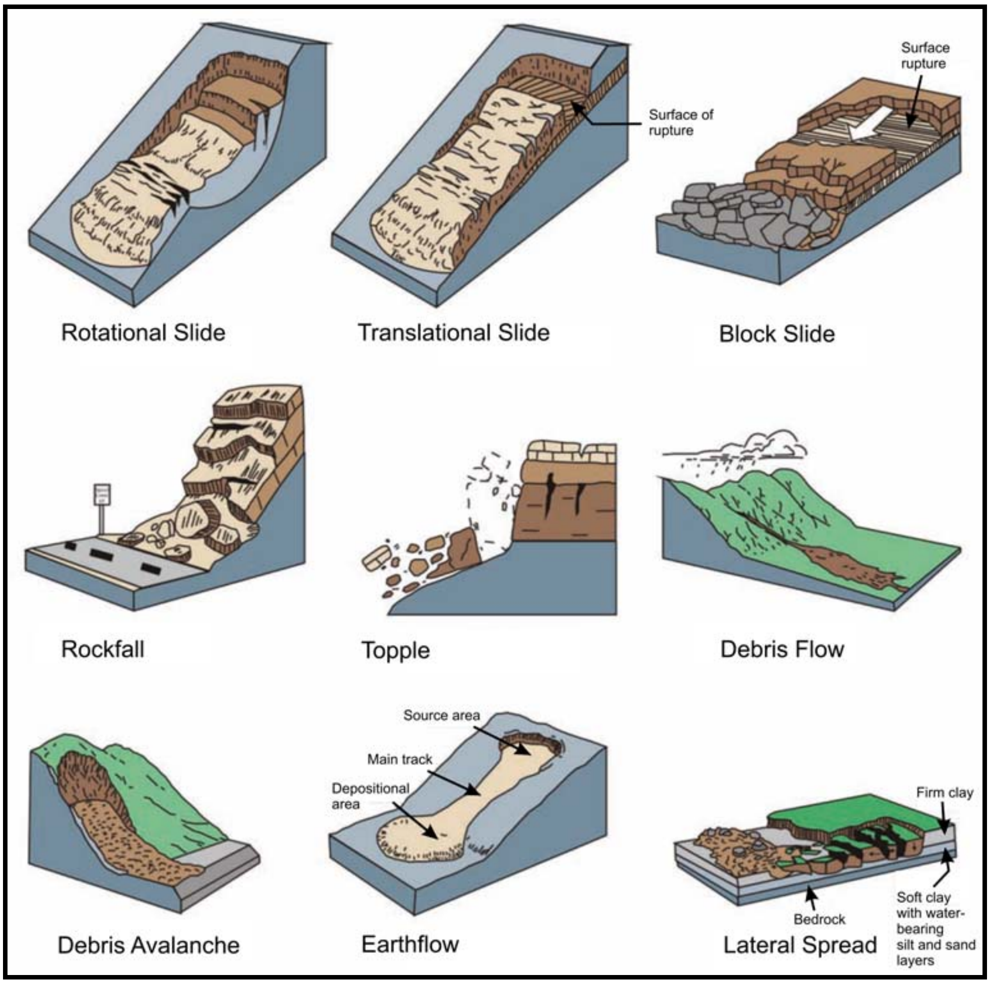

Figure 5.2: Different Types of Landslides. Modified from Highland, (2004) as cited in Saunders & Glassey (2007).

5.2.2 Causes and Triggers of Landslides

Slopes can become susceptible to landslides through a number of geological, morphological and human causes (Table 5.2). However, an external trigger generally initiates actual failure (Wieczorek, 1996). The most common natural triggers include intense rainfall, rapid snowmelt, water level change, volcanic eruption and earthquake shaking (ibid). However, not all landslides are caused by an obvious trigger; sometimes a combination of slope instability causes can initiate failure. Within New Zealand, the most common triggers of landslides are intense rainfall and large earthquakes (Crozier, 2007).

Table 5.2: Geological, morphological and human causes of slope instability. Modified from Cruden & Varnes (1996) as cited in Highland (2004).

1. Geological Causes • Weak or sensitive materials • Weathered materials • Sheared, jointed, or fissured materials • Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth) • Contrast in permeability and/or stiffness in materials
2. Morphological Causes • Tectonic or volcanic uplift • Glacial rebound • Fluvial wave, or glacial erosion of slope toe or lateral margins • Subterranean erosion (solution, piping) • Deposition loading slope or its crest • Vegetation removal (by fire, drought) • Thawing • Freeze-and-thaw weathering • Shrink-and-swell weathering
3. Human Causes • Excavation of slope or its toe • Loading of slope or its crest • Drawdown (of reservoirs) • Deforestation • Irrigation • Mining • Artificial vibration • Water leakage from utilities

5.2.2.1 Landslides and water

Slope saturation, by intense rainfall, snowmelt or a change in water level, is the primary cause of landslides. Heavy and prolonged rainfall during a storm is the most common cause of saturation, generating an increase in pore water pressures within the soil. This fluid pressure adds buoyancy to the slope and decreases the resistance to movement, thus triggering slope failure (Wieczorek, 1996). Landslides generated in this manner are generally shallow in nature and include debris and earth flows. An increase in pore water pressures can also be caused by snowmelt, which becomes significant, particularly if it is rapid, due to a sudden increase in temperature and when it is accompanied by rainfall (ibid). Intense rainstorms (100 mm or more in 24 hours) are the most common cause of slope saturation within New Zealand (Crozier, 2007).

Landslides can also be triggered by sudden changes in water levels adjacent to a slope. For example, if the water level in a lake was to drop suddenly, the groundwater level within an adjacent slope may not lower itself quickly enough, resulting in a relatively high water table. Hydraulic pressures then working within the slope can cause instability (Wieczorek, 1996). Undercutting of a slope by a river or waves can also trigger landslides.

5.2.2.2 Landslides and Earthquakes

Earthquakes are another major trigger of landslides in New Zealand and are capable of generating all landslide types. The maximum area likely to be affected by landslides depends on the depth and magnitude of the earthquake, along with local geological conditions (Keefer, 1984). In general, the maximum area ranges from 0 km^2 for a magnitude 4 event to 500,000 km^2 for a magnitude 9.2 event (ibid). Falls and slides are initiated by the weakest shaking, whereas more coherent, deeper-seated events require stronger shaking (ibid). Table 5.3 summarises the relationship between Modified Mercalli Intensities and landsliding.

Weakly cemented rocks, closely fractured rocks, residual and colluvial sands, cemented sands, granular alluvium and deltaic deposits are among materials most susceptible to failure during earthquakes (Keefer, 1984).

Table 5.3 Landslides likely to be generated during intensities of MM6 to MM10. Modified from Cox & Barrell, (2007).

MM 6	A few very small ($10^3 m^3$) soil and surface material landslides and rockfalls occur.
MM 7	Small falls of sand and gravel banks. Some fine cracks appear in sloping ground and ridge crests. Rockfalls from steep slopes and cuttings are common. A few small to moderate landslides (10^3-$10^5 m^3$) occur on steeper slopes, and there are instances of liquefaction at susceptible sites.
MM 8	Cracks appear on steep slopes and in wet ground. Significant landsliding in susceptible areas, with widespread small to moderate (10^3-$10^5 m^3$) and some large slides.
MM 9	Conspicuous cracking of flat and sloping ground. General landsliding on steep slopes. Many small to large landslides (10^3-$10^6 m^3$), and some very large ($>10^6 m^3$) landslides and debris avalanches – forming dams and lakes in narrow valleys.
MM 10	Widespread cracking of flat and sloping ground. Widespread and severe landsliding on sloping ground. Very large rock masses ($>10^6 m^3$) displaced on steep mountain faces and coastal cliffs.

5.2.3 Consequences of Landslides

Landslides have caused countless casualties and huge economic losses worldwide. They are capable of killing or injuring people and animals, destroying or damaging developments, and agricultural and forest lands, and negatively affecting water quality in rivers and streams (Schuster, 1996). Despite advancements in landslide recognition, prediction, mitigative measures and warning systems, landslide activity is increasing worldwide and is expected to continue to do so (ibid). This is mainly due to increasing population pressures leading to development of landslide-prone areas, ongoing deforestation, and changes in climate patterns resulting in increased regional precipitation (ibid).

Not all landslide types present the same level of danger. For example, a singular rock fall is less likely to generate the same impact as a large rock avalanche. However, the consequences of landslides are not only a function of their size, but also of their speed. For example, a small but rapid debris flow is capable of causing complete destruction, whereas a larger slope movement of moderate velocity oftens allow for evacuation and avoidance (Cruden & Varnes, 1996). The probable destructive significance of different landslide velocities, was examined by Cruden and Varnes (1996) and their findings are summed up in Table 5.4.

Table 5.4: The consequences of different landslide velocities. Modified from Cruden & Varnes, (1996): 50.

Velocity Class	Description	Typical Velocity	Consequences
7	Extremely Rapid	≥5 m/sec	• Catastrophe of major violence, • Buildings destroyed by impact of displaced material, • Many deaths, • Escape unlikely.
6	Very Rapid	3-5 m/sec	• Some lives lost, • Velocity too great to permit all persons to escape.
5	Rapid	1.8 m/hour – 3 m/sec	• Escape evacuation possible, • Structures, possessions, and equipment destroyed.
4	Moderate	13 m/month – 1.8 m/hour	• Some temporary and insensitive structures can be temporarily maintained.
3	Slow	1.6 m/year – 13 m/month	• Remedial construction can be undertaken during movement, • Insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase.
2	Very Slow	16 mm/year – 1.6 m/year	• Some permanent structures undamaged by movement.
1	Extremely Slow	Up to 16 mm/year	• Imperceptible without instruments; construction possible with precautions.

In alpine terrain, which is characterised by hard rock and steep, high slopes, landslides are dominated by huge rock avalanches, rock slides, rock falls and debris falls (Crozier, 2007). The speed of these types of landslides typically range from very rapid to extremely rapid, and are capable of travelling many kilometres (Cruden & Varnes, 1996). Therefore, because of their volume, speed and potential travel distance, many alpine landslides are considered catastrophic and are responsible for widespread death and destruction in populated regions of the world (Crozier, 2007). Lakes Lyndon, Coleridge and Tekapo are all in part, surrounded by steep, high slopes and this is of concern. As areas, such as these, become more populated, the potential hazard from landslides increases.

Injuries, fatalities and property damage can occur directly from landslide impact or from indirect measures, such as flooding from a landslide-generated tsunami or from a landslide dam outbreak. Landslides that directly enter into a lake can generate waves, which can be catastrophic (refer to section 4.7.4). In May and August of 1992, successive rock avalanches fell into Maud Lake from Mt Fletcher, at the head of the Godley River. The first and largest rock avalanche generated a 10 m high wave, which entered into the Godley River, adding nearly 8 x $10^6 m^3$ of water to Lake Tekapo. A 7 m high wave is thought to have been generated by the second avalanche (Hicks & Campbell, 1998). There was no threat to people or property from these waves due their occurrence in a remote area, but it illustrates what can happen in susceptible areas. Rivers or streams can also be blocked by landslide debris, causing water upstream to pond and form a lake. These lakes can pose great threats to communities downstream as most dams formed in such way seldom last more than a few days (ibid).

Countless landslides have occurred in and around the central Southern Alps. Whitehouse (1983) and Whitehouse and Griffiths (1983) documented the distribution of large rock avalanches within this area (Figure 5.3). The expected frequency of one of these large mountain collapses ($>10^6 m^3$) is thought to be one per 20 to 30 years (McSaveney, 2002). However, in any given specific region, such as around one of the lake areas, the frequency of such a large event decreases, and in comparison with the length of a human lifetime, this occurrence is low. Therefore, people are often lulled into a false sense of security concerning landslide hazards (Turner & Jayaprakash, 1996).

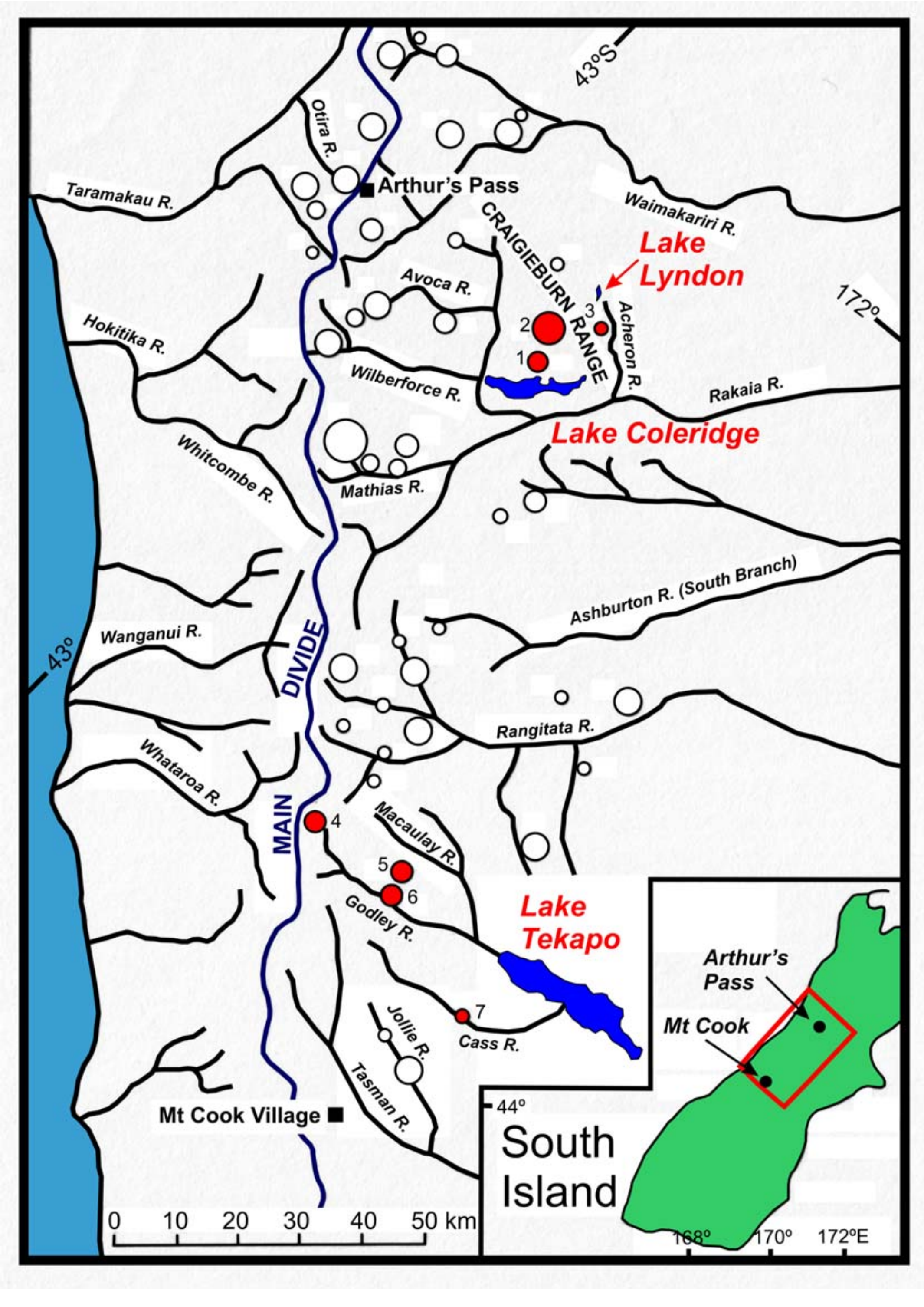

Figure 5.3: The distribution of large rock avalanches in the central South Island. Rock Avalanches mentioned in the text include: 1 – Lake Coleridge Rock Avalanches, 2 – Craigieburn Rock Avalanche, 3 – Acheron Rock Avalanche, 4 – Mount Fletcher Rock Avalanches, 5 & 6 – Godley River Avalanches and 7 – Cass River Rock Avalanche. Source: Modified from Whitehouse & Griffiths, (1983): 274.

5.3 History of Landslides around Lakes Lyndon and Coleridge.

A number of significantly large landslides have occurred in the vicinity of Lakes Lyndon and Coleridge within the last 10,000 years (Figure 5.4). Fortunately, no really large events have occurred in historical times, but given the surrounding topography of the lakes and the regional seismicity, the likelihood of future large events is high. Past large landslides, which have occurred in the area are summarised.

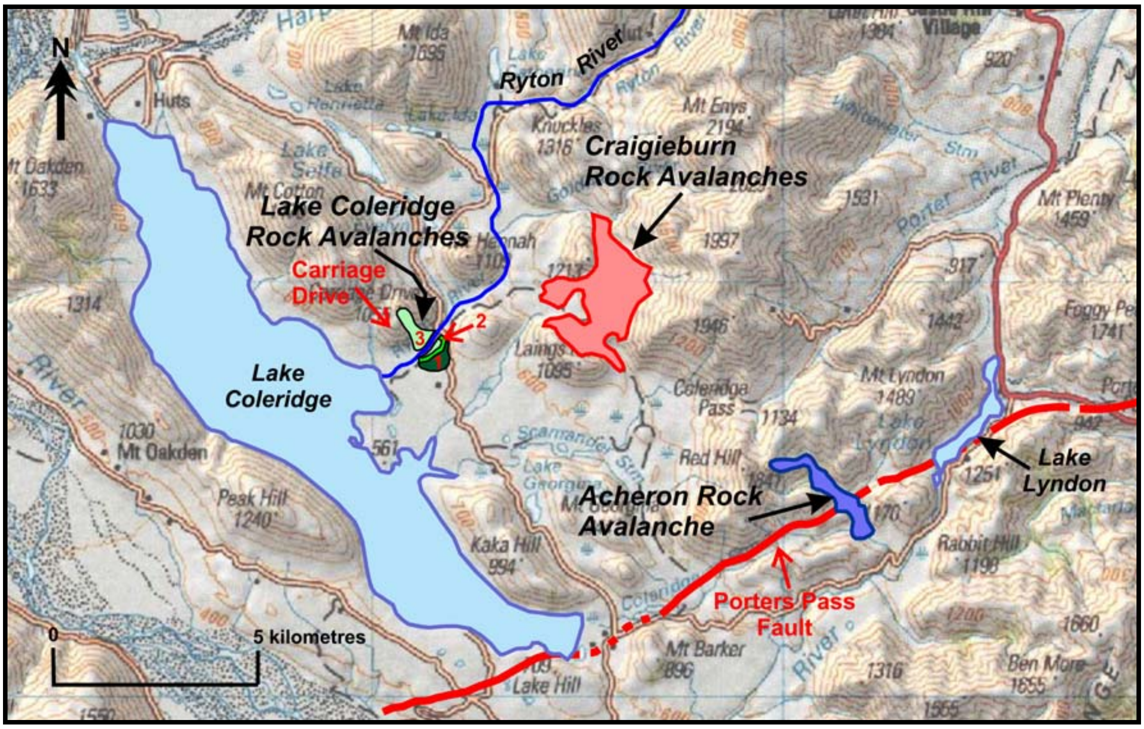

Figure 5.4: Location of significant landslides around Lakes Lyndon and Coleridge.

5.3.1 The Lake Coleridge Rock Avalanches

The deposits of three rock avalanche events have been identified at the base of the south-eastern slope of Carriage Drive, near the mouth of the Ryton River (Lee, 2004). These three events are known as the Lake Coleridge Rock Avalanches (LCRA) 1, 2 and 3, with $LCRA_1$ being the eldest event. The avalanche deposits were first noted by Whitehouse (1981; 1983) and Whitehouse and Griffiths (1983) as a single event thought to have occurred about 150±40 years ago. A further study by Lee (2004), determined that three separate events had actually occurred. A summary of the avalanche characteristics are summed up in Table 5.5.

Table 5.5: Main characteristics of the Lake Coleridge Rock Avalanches. Source: Lee, (2004):145.

Rock Avalanche	Age (years B.P.)	Deposit Volume (10^6m^3)		Runout Distance (m from source)
		Present Day	Original	
LCRA1	Maximum of 9,720±750	5.1	12.5	1,780
LCRA2	668±36	0.37	0.65	1,350
LCRA3	Undated	<0.1?	~0.1?	<1,340?

As stated in Table 5.5, the first rock avalanche is thought to have occurred 9720±750 years ago, after the retreat of Acheron 3 ice from the area (refer to chapter 2). A huge volume of debris cascaded down from Carriage Drive and was deposited right across the Ryton River. This damming of the river led to the formation of a lake, which covered an area of about 1.1 km^2 and had a volume of about 17 x 10^6m^3 (Lee, 2004). The lake is thought to have existed for a number of years before the river was able to overtop and downcut through the deposits (ibid).

The second rock avalanche, which occurred around 668±36 years ago, was much smaller than the first event (Table 5.5). The debris from this event followed the same runout path as $LCRA_1$, and due to its smaller size, was confined to a gully formed by the Ryton River, within the $LCRA_1$ deposits (Lee, 2004). This event also blocked the Ryton River. A lake with a volume of approximately 2.3 x 10^6m^3 is thought to have existed for about two weeks before overtopping the dam and creating a large outwash flood (ibid). The age of the third and smallest event, $LCRA_3$ has not been constrained. However, according to Lee, it is thought to have occurred very soon after the second event.

Carriage Drive is composed of sub-vertical argillite beds, which appear to have been toppling ever since the removal of Acheron 3 ice from the area c. 10,000 years ago (Lee, 2004). Toppling makes the slope prone to failure and is therefore thought to have contributed to the cause of each rock avalanche event. Seismic shaking is, however, believed to have been the main trigger of the rock avalanches, despite no specific seismic events being assigned to each rock avalanche event.

5.3.2 The Craigieburn Rock Avalanches

Two immense rock avalanches have fallen from the summit and western slopes of a former peak within the Craigieburn Range, east of Lake Coleridge. Whitehouse (1981) identified two sources from which the rocks fell and concluded, from weathering rind data, that the timing of the two events was more or less simultaneous at c. 350±90 years ago (now c. 375±90) (Whitehouse, 1983). However, weathering rind dating carried out by Orwin (1998) revealed that the two events were actually quite separate, with one event occurring at approximately A.D.1422±96 (586±96 years ago) and the other at A.D.1632±55 (376±55 years ago). This latter date coincides with the date obtained by Whitehouse. The avalanche deposits, which are spread over 4 km^2, have an estimated volume of 500 x $10^6 m^3$ and are up to 300 m thick in some places (Whitehouse, 1981).

5.3.3 The Acheron Rock Avalanche

The Acheron Rock Avalanche is another major slope failure in the vicinity of Lakes Coleridge and Lyndon. It is located immediately south-west of Lake Lyndon and lies over a Holocene trace of the active Porters Pass Fault (Figure 5.4). The rock avalanche, which advanced at a maximum speed of 140 to 160 km per hour, travelled a total distance of 3500 m, terminating about 700 m from Lyndon Road (Smith, 2003). The deposits are spread over an area of 72,000 m^2 with an estimated volume of 8.9 x $10^6 m^3$ (ibid). However, taking into consideration subsequent dilation of the deposit and debris accumulation on top of the avalanche deposit, the volume of the initial failed rock mass is thought to have been approximately 7.5 x $10^6 m^3$ (ibid).

Burrows (1975) first radiocarbon dated the deposits at around 500±69 years B.P. (1475±69 A.D.) and subsequent dating of the deposits yielded an average age of 1486±79 years A.D. (Howard, 2001). However, the most recent study of the Acheron Rock Avalanche, which was conducted by Smith (2003), yielded quite different deposit ages. Wood samples were extracted from the contact between the underlying terrace surface and the avalanche deposit. Dates ranging from 1370 to 1100 years B.P. were acquired from the wood samples, with the most reliable sample dated at 1152±51 years B.P. Smith believes that disturbance of the surface of the rock avalanche deposit has led to incorrect dates being obtained in the earlier studies.

The rock avalanche source area is composed of massive sandstone and thinly bedded mudstone sequences, which dip steeply north into the centre of the source basin (Smith, 2003). Steep, south-dipping toppling failure planes were also identified and it is the interaction of these with the bedding that is believed to have made the slope susceptible to failure (ibid). The principal trigger of the rock avalanche is, however, believed to have been an earthquake, such as one on the Porters Pass Fault, or the Alpine Fault. A study by Howard *et al.* (2005) revealed that six earthquakes had occurred during the Holocene on the eastern segment of the Porters Pass Fault (refer to section 4.3.1.5), over which the Acheron Rock Avalanche lies. One of these events has been dated at 800 to 1100 years B.P., which coincides with a date for the rock avalanche of 1152±51 years B.P. (Smith, 2003). The Alpine Fault, which is thought to have ruptured around 1010±50 years ago (the Round Top event), may have also triggered the rock avalanche (ibid).

5.4 History of Landslides in and around Lake Tekapo

There have been a number of slope failures identified within and around Lake Tekapo (Figure 5.3). Upton and Osterberg (2007) carried out a seismic survey of the lake in 2001 and identified at least fifteen separate mass movement deposits within the lake. Other slope failures have been identified within the vicinity of the lake, but none have been studied in much detail. A number of landslide deposits have been identified on the recently published Aoraki QMAP by Cox and Barrell (2007).

5.4.1 Landslides within Lake Tekapo

At least fifteen mass movement deposits were identified on the lakebed by Upton and Osterberg (2007). All are located next to areas of high relief, such as the lakeshores or Motuariki Island, and have volumes on the order of 6 x $10^6 m^3$. Seven identified mass movement events in the southern half of the lake are believed to have occurred at the same time at c. 1720±344 years B.P. Another set of mass movement deposits were identified in the north eastern part of the lake, yielding an age of c. 2810±562 years B.P. Given these two distinct groups of deposits, the most likely trigger was seismic shaking. There are a number of local faults, such as the Irishman Creek Faults and Fox Creek Faults, which may have triggered these events (refer to Chapter 4). However, more distant faults, such as the Alpine Fault or the Marlborough Fault System may have also triggered the slope failures. It is not known whether or not these landslides generated tsunami or seiches, but given their size, there is a high possibility that they did.

5.4.2 Landslides around Lake Tekapo

A few rock avalanches have been identified near the Godley River, about 25 km north of Lake Tekapo. For example, a rock avalanche at the junction of McKinnon Stream and the Godley River was identified by Whitehouse and Griffiths (1983) (Number 6, Figure 5.3). The deposit volume is approximately 21 x $10^6 m^3$ and is thought to be c. 1700±440 years old B.P. Deposits from another rock avalanche, the Cass River Rock Avalanche has been identified half way up Cass River (Number 7, Figure 5.3). Rock avalanches have also occurred for many decades off Mt Fletcher, which is situated to the north-west of Maud Glacier at the head of the Godley River (McSaveney, 1993). Two major rock avalanches occurred off the mountain in May and September of 1992 (Number 4, Figure 5.3). Both of these events had the effect of sending a flood wave down the Godley River into Lake Tekapo (ibid). The lake levels are thought to have increased by a maximum of 90 mm, which does not represent a major hazard, but nevertheless it illustrates the secondary effects from landslides.

5.5 Potential for Future Landslides around Lakes Lyndon and Coleridge.

5.5.1 Lake Lyndon

Lake Lyndon is surrounded primarily by steep facing slopes. The source areas for some of the alluvial fans, which enclose the lake, contain large volumes of scree material, which could be triggered either by intense rainfall or by earthquake shaking (Figure 5.5).

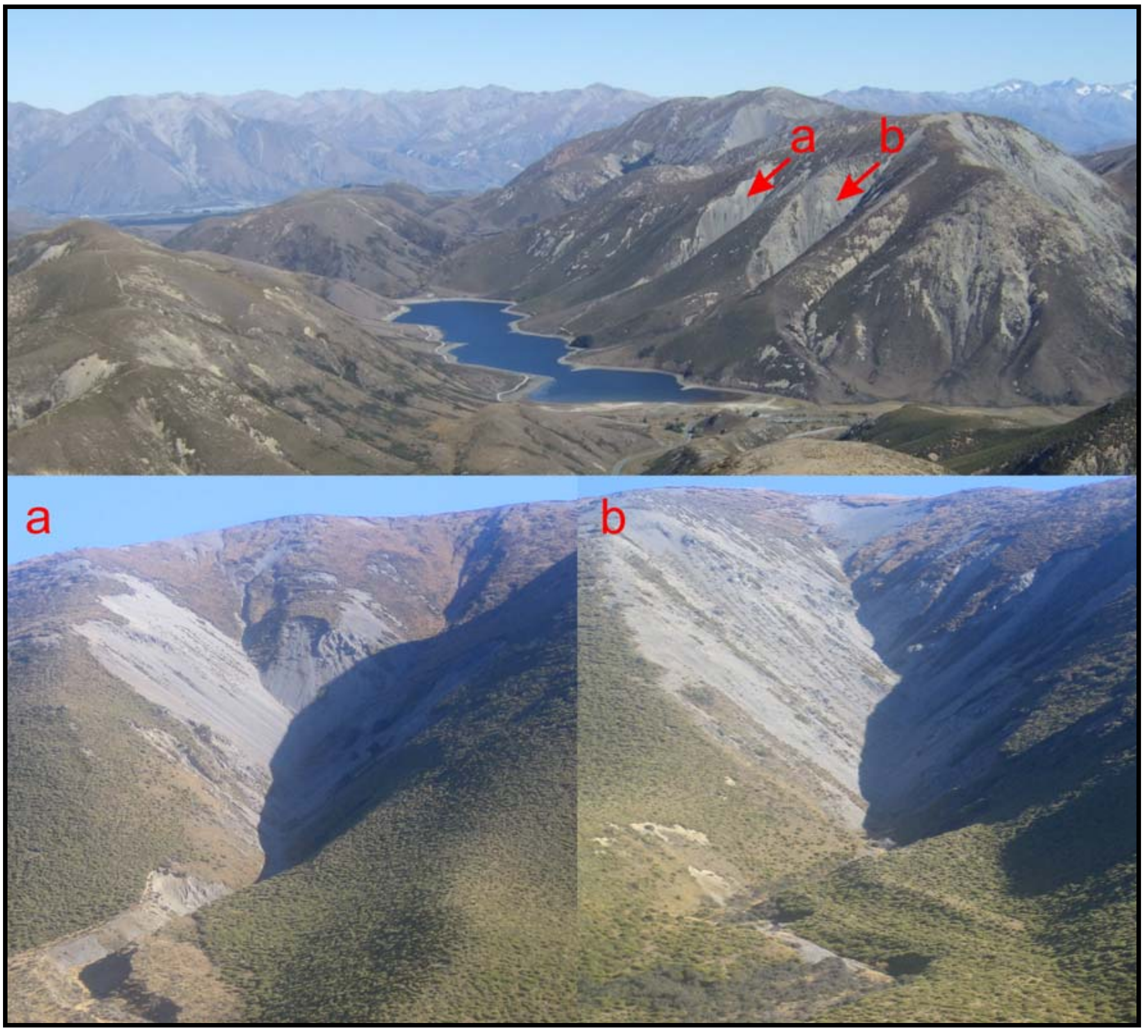

Figure 5.5: The steep-facing topography surrounding Lake Lyndon and the source areas for two major alluvial fans (a & b).

All of the slopes surrounding Lake Lyndon are at significant risk of earthquake-induced instability under moderate to strong earthquake shaking (i.e. MM intensities of MM7 or greater) (Figure 5.6) (Yetton & McCahon, 2006). MM7 intensities are expected to affect the Lyndon area in any given 50 year period so the threat from landslides around the lake is very high.

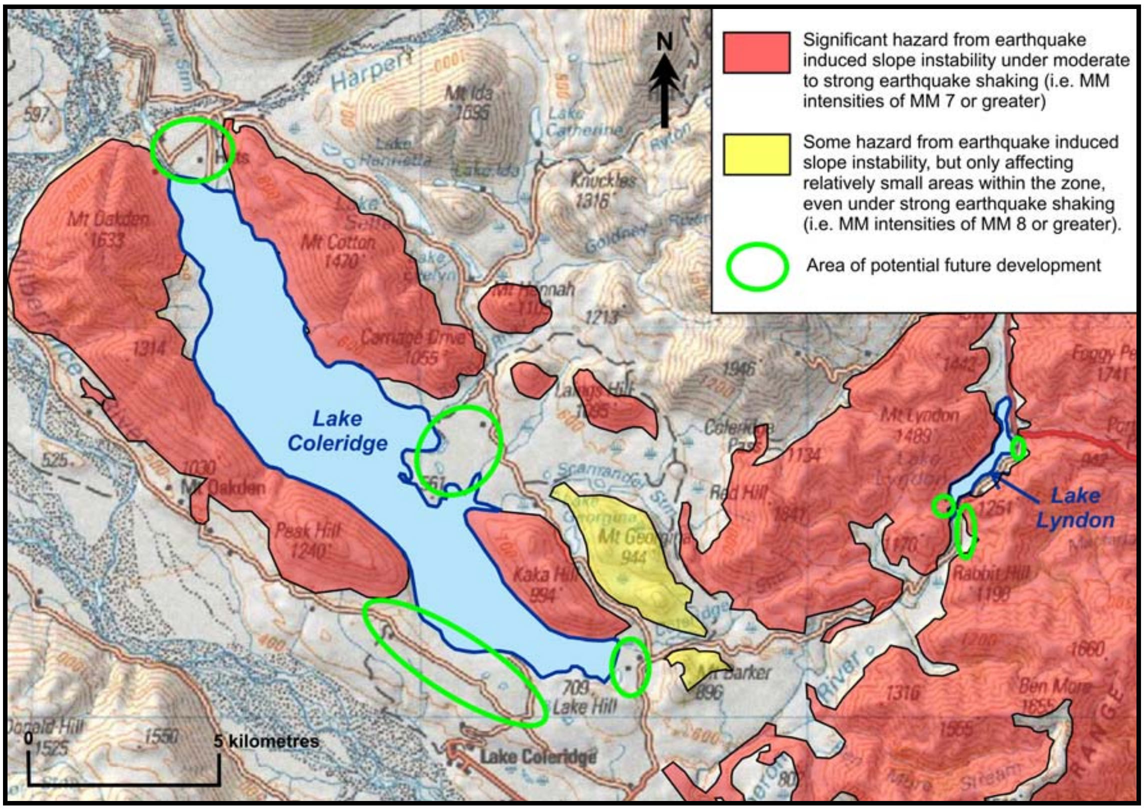

Figure 5.6: Potential earthquake induced slope instability zones around Lakes Lyndon and Coleridge.

Lyndon Road and Lake Lyndon Lodge are at risk from direct landslide impact and also from the impact of a landslide induced wave (Figure 5.7). The size of a possible wave has not been constrained but given that the road and lodge are within only a few metres elevation of the lake water level and are very close to the lake edge, it would not take a very large wave to cause damage. Slides into shallow water are generally more critical than those that occur in deep water because more extreme wave heights can be generated (Masson *et al.*, 2006).

Figure 5.7: The location of Lyndon Road and Lake Lyndon Lodge at Lake Lyndon.

5.5.2 Lake Coleridge

Lake Coleridge is also predominantly surrounded by steep-facing slopes, which are susceptible to future landsliding (Figures 5.6 and 5.8). These slopes are at significant risk from earthquake-induced instability under moderate to strong earthquake shaking (i.e. MM intensities of MM7 or greater) (Yetton & McCahon, 2006) and as noted in section 4.7.1 of Chapter 4, the region is expected to experience MM7 shaking intensities at least once in any given 50 year period. Therefore, there is an extremely high chance of slopes around the lake failing within the next 50 years. Areas of possible future development around the lake are not only threatened by direct landslide impact but also from landslide-induced tsunami and from landslide dam outbreaks. Slopes of particular concern include Peak Hill, the Harper Fan, and the slopes on either side of the Ryton River.

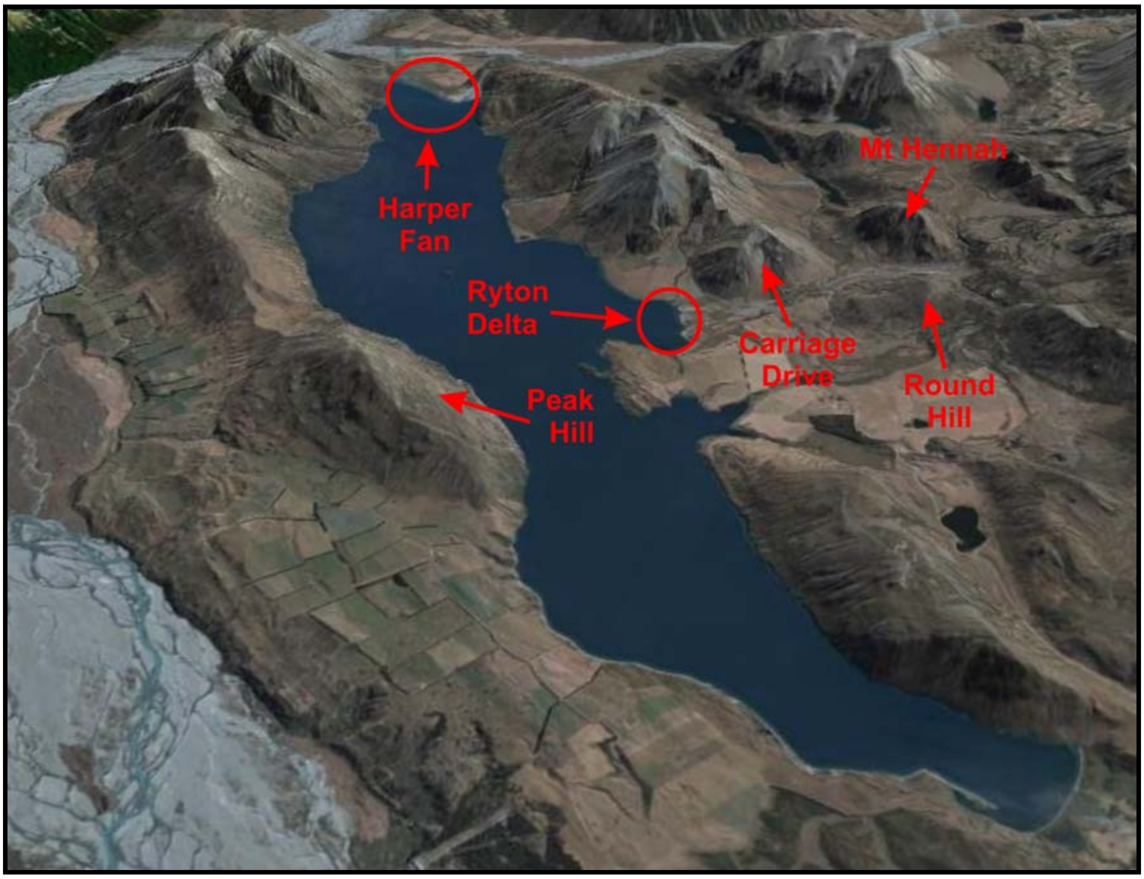

Figure 5.8: Lake Coleridge and its surrounding steep topography.

5.5.2.1 Landslide-induced tsunami

Landslides in and around Lake Coleridge are capable of generating tsunami if they enter the lake. The potential size of such a wave has not been constrained, but the lake has a very similar bathymetry to that of Lituya Bay, which has had waves of up to c. 524 m produced by landslides (refer to section 4.7.4 in Chapter 4). Modelling of other landslide tsunami has also shown that extreme wave heights of hundreds of metres are possible (Masson *et al.*, 2006). Landslide-generated tsunami typically have very large run-ups close to the landslide site and limited far-field effects (ibid). Slopes which may potentially cause a landslide-induced tsunami are discussed.

5.5.2.1.1 The Harper Fan

Figure 5.6, which has been modelled on Yetton & McCahon's work, does not take into account the possibility of lateral spreading, which may occur at lake and stream margins. Therefore, areas such as the Harper Fan may also be at substantial risk of partially collapsing during earthquake shaking. Masson *et al.* (2006) noted that submarine deltas and fans of large rivers are subject to widespread landsliding. The occurrence of such landslides is not greatly affected by slope gradients, except at the shallowest gradients where only a few landslides occur (ibid). Most of the lateral slopes of Lake Coleridge are very steep (between 50º to 60º) except for the Harper Fan, which slopes up to 16º and the Ryton Delta, which typically has slopes of less than 5º.

Elevated pore pressures from processes such as earthquake shaking are a key factor in landslide occurrence, and historical evidence suggests that the majority of submarine landslides are triggered by earthquakes (ibid). Therefore, all deltas and subaqueous fans must be treated as being at high risk of failing during earthquake shaking. Generally, slopes prone to submarine landslides show a history of landsliding (ibid). However, in the case of areas such as the Harper Fan it is not known whether past landslides have occurred here. Subaqueous landslides are significant for their tsunami-generating potential.

5.5.2.1.2 Peak Hill

Another slope of particular concern is the north-facing flank of Peak Hill. A large section of this slope has been identified as being affected by some form of gravitational slope movement. Figure 5.9 shows how this area appears to have slumped. If this slope were to collapse under heavy rainfall or earthquake shaking, it could generate a wave, which could threaten low lying areas around the lake, such as Ryton Bay, where development has been proposed (refer to section 3.4.3 in Chapter 3).

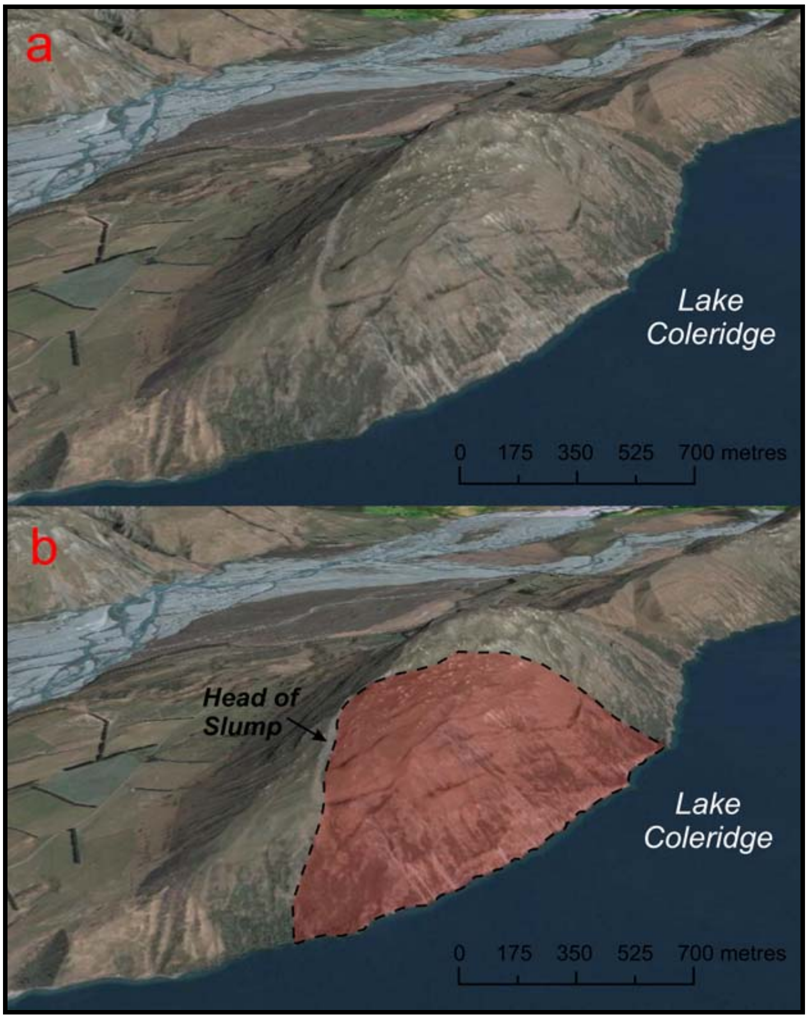

Figure 5.9: Peak Hill on the shores of Lake Coleridge. The top picture, a, shows the slope in its natural state and the bottom picture, b, highlights the approximate area under the effect of gravitational slope movement.

5.5.2.2 Landslide Dams and the Ryton River

Landslides also have the ability to block or dam a river, causing water upstream to pond and form a lake. Such lakes are huge threats to downstream development as they seldom last long. The area of greatest concern from a landslide dam forming is along the Ryton River. At least two past rock avalanches are known to have blocked the Ryton River and these are the Lake Coleridge Rock Avalanches 1 and 2 (refer to section 5.3.1). The largest of these lakes is thought to have had a volume of c. 17 x $10^6 m^3$ (Lee, 2004), which upon sudden failure would have most probably flooded the lower reaches of the Ryton River where a camping ground exists today (Figure 5.10) .

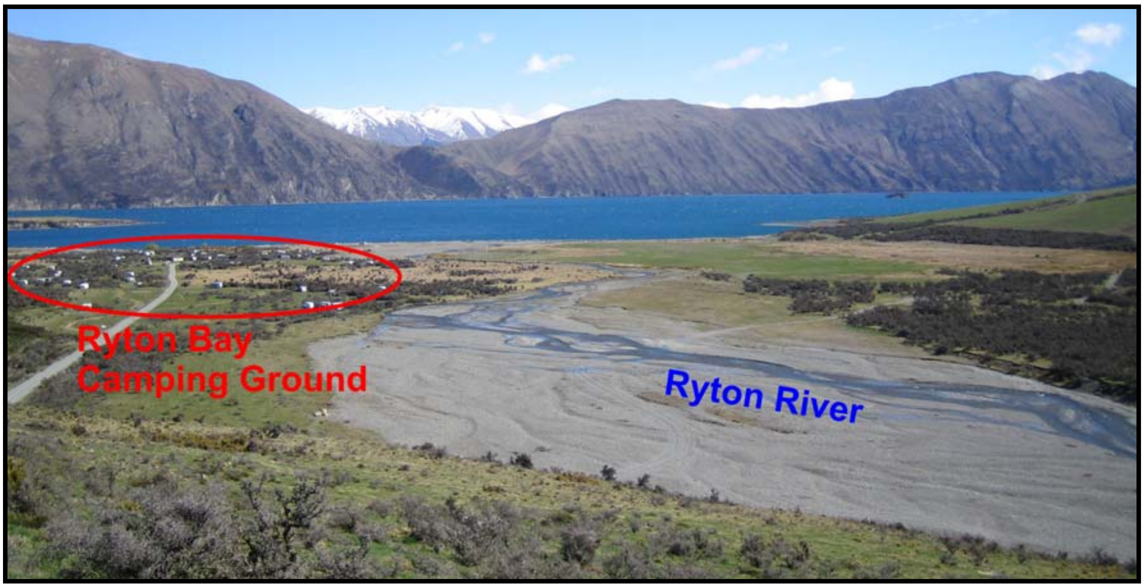

Figure 5.10: The lower reaches of the Ryton River. The Ryton Bay Camping Ground is situated on the flood plain of this river.

The likelihood of a future rock avalanche from Carriage Drive is very high. It is evident that large volumes of material are present in the source area, which could feed a number of future events. A wedge block of displaced material was identified by Lee (2004) and is considered to be the likely source material for a future rock avalanche (Figure 5.11).

Figure 5.11: The Lake Coleridge Rock Avalanche source area on the south-eastern side of Carriage Drive. The wedge block of displaced material, identified by Lee,(2004), is outlined in red.

This block, which is estimated to be c. 35,000 ± 5000 m^3 in volume, has the potential to once again dam the Ryton River. The top of the source area consists of sub-vertical Torlesse beds along which dilation is occurring (ibid). Therefore, future dilation of the rock mass, earthquakes or storm events could trigger a future landslide. The threat of a landslide damming the Ryton River not only comes from Carriage Drive but from other slopes next to the river, such as from Round Hill and Mount Hennah.

The larger the landslide, the larger a possible dam may be, and the larger the dam, the longer water has to accumulate behind it as a lake. If a large dam were to fail, there would be widespread flooding to low elevated land adjacent to the river, including where the current Ryton Bay camping ground exists and to where future Ryton Bay development has been proposed.

5.6 Potential for Future Landslides around Lake Tekapo

Lake Tekapo is surrounded by uplifting mountain ranges with steep slopes. The Torlesse Supergroup rocks that make up the ranges are pervasively fractured, a common cause of slope instability. Therefore, as uplift continues, landslides will continue to occur. A few slopes bordering the lake are at significant risk from earthquake-induced landsliding under moderate to strong shaking (i.e. MM intensities of MM7 or greater) (Figure 5.12). The area is expected to experience this level of shaking about once every 150 years (refer to section 4.7.1 of Chapter 4). Currently, the development around the lake is concentrated at its southern end. The main threat to the development in this area comes from Mount John, which appears to have two sections affected by gravitational slope movement. As other areas around the lake become further developed, the threat from even minor landslides increases. Apart from Mount John, the other major areas of potential slope instability are the north-western mountains and the Godley River delta.

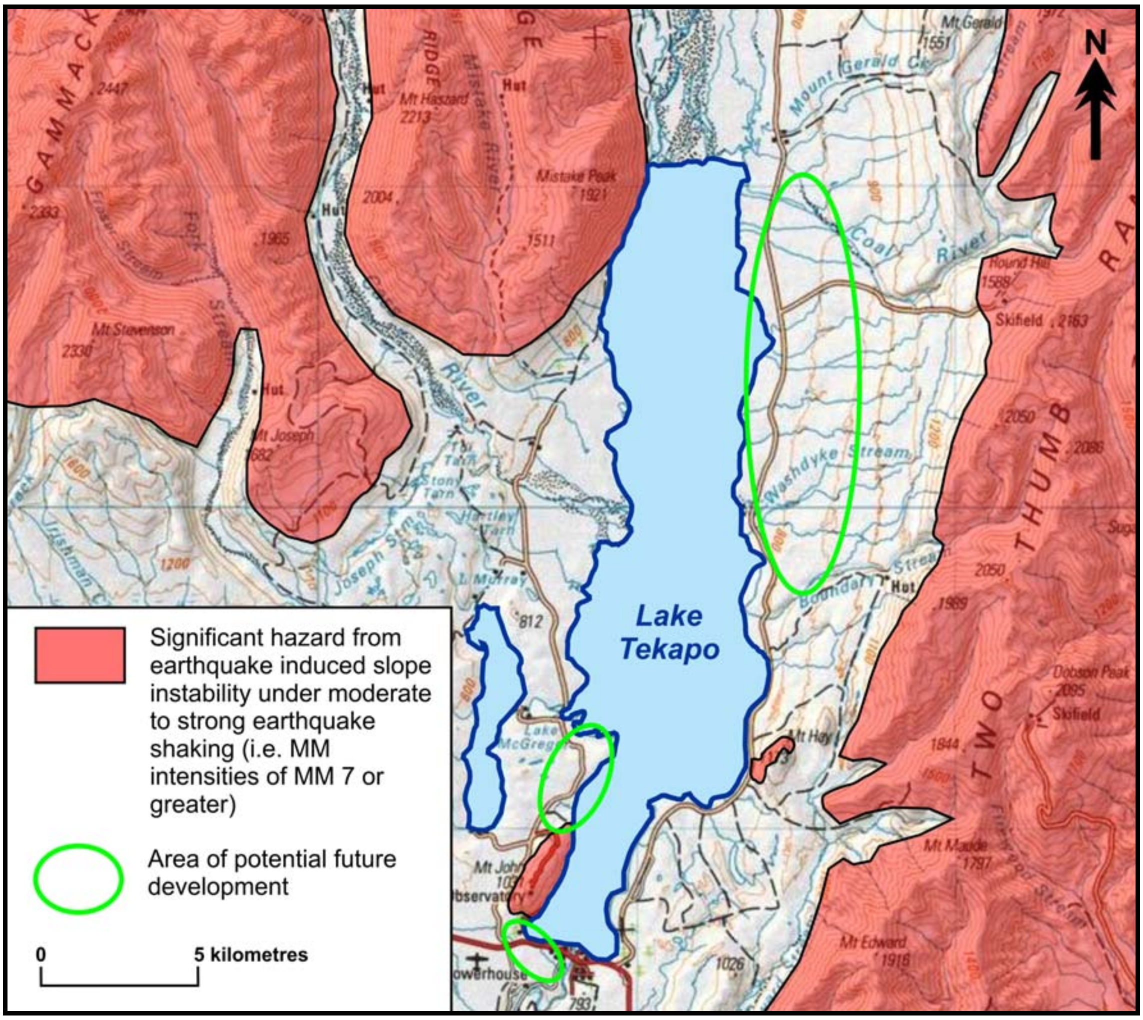

Figure 5.12: Slopes around Lake Tekapo at significant risk from earthquake-induced instability under moderate to strong earthquake shaking.

5.6.1 Mount John

Cox and Barrell (2007) identified two sections of Mount John that were affected by gravitational slope movement (Figure 5.13). The first section is the southern most end of the mountain, which appears to have slumped. This is of particular concern due to new development (Alpine Springs and Spa Winter Park) occurring at the base of this slope (Figure 5.14). If failure were to occur, a few million cubic metres of material could potentially be activated. However, the slope has been intact since deglaciation around 10,000 years ago and has, therefore, withstood many large earthquakes and may be stable. Therefore, a detailed site investigation should be carried out to determine how stable it is. A smaller section of hillside on the eastern side of Mt John is also thought to be affected by gravitational slope movement. As it is located above the lake, no direct consequences will take place if it were to collapse, unless people were on the slope at the time. However, a series of waves may be generated, which could flood low-level areas of the township.

Figure 5.13: Areas of Mount John affected by gravitational slope movement (as indicated in red). The boundaries of the two areas are approximate only.

Figure 5.14: Development at the base of the southern slope of Mount John.

5.6.2 The Godley River Delta

About 55 per cent of the total sediment input into Lake Tekapo enters via the Godley River, which as a result, has an extensive delta (Graham *et al.*, 2005). Low angle topset beds are present across the full width of the 3 km valley. A sharp break then exists between the top of the delta, where the topset beds are deposited, and the convex delta slope, which grades southward and merges with the lakebed, about 6 km away (Pickrill & Irwin, 1983). The steepest slopes on the upper delta are about 17º (ibid).

During winter, shallow slides of sandy muds reworked from the top of the delta are common, occurring to depths of at least 65 m (Pickrill & Irwin, 1983). In addition to these semi-annual shallow slides, the entire 20 km^2 of delta slope is subject to reworking by infrequent, deeper-seated rotational failures (ibid). Pickrill and Irwin (1983) identified this vulnerability to large rotational failure and constructed a longitudinal profile of the delta, illustrating the features typical of rotationally slumped beds (Figure 5.15).

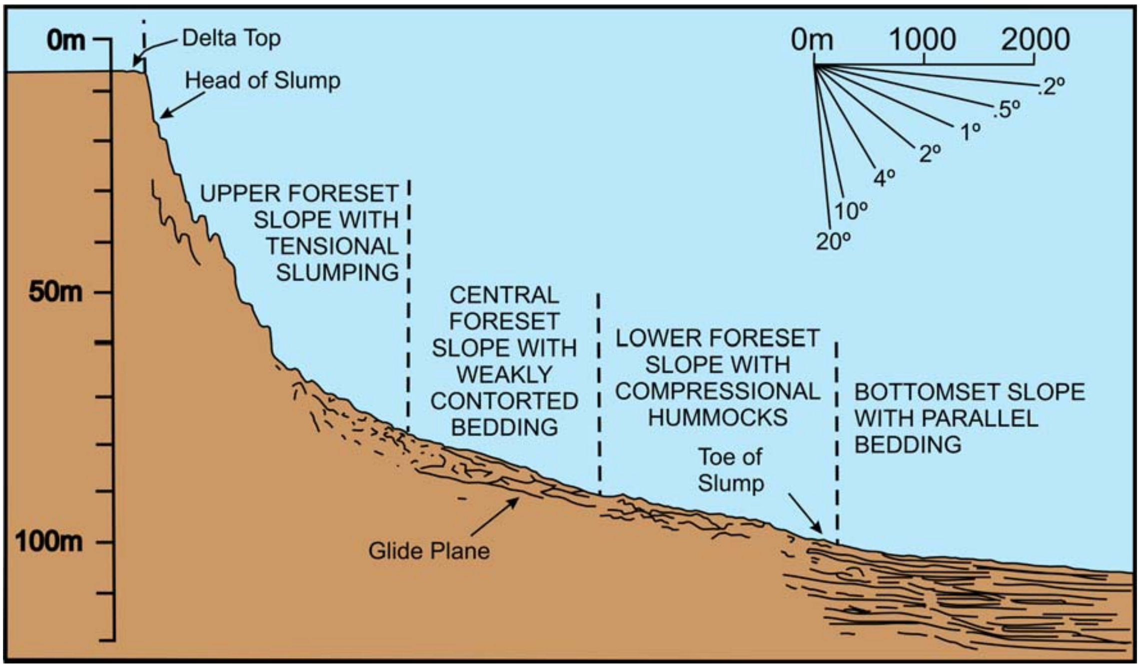

Figure 5.15: Longitudinal profile of the slumped beds of the Godley delta. Modified from Pickrill & Irwin, (1983): 68.

The head of the slump area is characterised by a pull-apart zone, with up to 17 slump terracettes and tensional depressions. Contorted bedding and hummocky folds at the base of the slope mark the toe of the slump. These characteristic signs of slumping are found on most of the delta slope, indicating that large volumes of sediment, on the order of $8 \times 10^6 m^3$, are capable of being redistributed downslope. Several different processes could trigger such an event.

Heavy sedimentation on the upper slope keeps the delta in a metastable, oversteepened condition (Pickrill & Irwin, 1983). Therefore, an uncharacteristic influx of sediment from, for example, a landslide entering the Godley River upstream, could overload the slope further and trigger failure. Overloading of the slope may also occur when the lake level is lowered, and the delta top and upper slope is exposed. When this occurs, sediment that is normally deposited on the delta top may be deposited on the top of the delta slope, subsequently overloading it. During times when the upper slope is exposed, such as in winter, failure may also be triggered by a loss in hydraulic support. Waves breaking against the slope can also cause the slope to slump (ibid). Lastly, earthquakes are also commonly known to cause landsliding, and given the regional seismicity of the area (refer to chapter 4), this is a likely threat.

The major hazards related to subaqueous landslides include the destruction of seabed/lakebed infrastructure, such as pipelines, the collapse of shore areas into the water, and landslide-generated tsunami. If part of the Godley delta were to collapse, the settlements around Lake Tekapo would be most prone to the effects of a possible subsequent tsunami. Where large volumes of material are involved, a subaqueous landslide could generate a wave ranging from a small event concentrated landward of the failure, to a mega tsunami on the order of tens of metres high (Bryant, 2001).

5.6.3 The North-western Slopes

The slopes to the north-west of Lake Tekapo are extremely steep (Figure 5.16). These slopes are subject to periodic rockfalls and if a large section were to collapse, large waves could be generated, flooding low-level areas, such as low-lying areas of

Richmond Station (within 10 m elevation of the lake level). Other low-level areas to the north and east of Lake Tekapo could also be at risk from flooding as a result of a landslide dam blocking either the Godley or Macaulay Rivers. The slopes on either side of these rivers are extremely steep right along their entire length. Even partial blockage of one of these rivers could divert the river flow enough so that low-level areas with development could be flooded.

Figure 5.16: Mistake Peak is situated on the north-western shores of Lake Tekapo. The Godley River, which drains into the northern side of the lake, is shown in the foreground.

5.7 Chapter Summary

- Landslides are common in the terrain around the Canterbury Lakes. Despite this, landslides have only caused a few deaths in the area, mostly due to there being few settlements in the mountainous terrain. In alpine terrain, which is characterised by hard rock and steep, high slopes, landslides are dominated by huge rock avalanches, rock slides, rock falls and debris falls. Due to their volume, speed and potential travel distance, many alpine landslides are considered catastrophic and are responsible for widespread death and destruction in populated regions of the world. Lakes Lyndon, Coleridge and Tekapo are all, in part, surrounded by alpine terrain and as areas, such as these, become more populated, the potential hazard from landslides increases. Injuries, fatalities and property damage can occur directly from landslide impact or from indirect measures, such as flooding from a landslide-generated tsunami or from a landslide dam outbreak.

- A number of significantly large landslides have occurred near Lakes Lyndon and Coleridge within the last 10,000 years, including the Lake Coleridge Rock Avalanches, the Craigieburn Rock Avalanches and the Acheron Rock Avalanche. Fortunately, no really large events have occurred in historical times, but given the surrounding topography of the lakes and the regional seismicity, the likelihood of future large events is high. There have also been a number of slope failures identified within and around Lake Tekapo. At least fifteen mass movement deposits have been identified on the lakebed and a few rock avalanches have been identified at the head of the Godley River, the most recent being the Mt Fletcher Rock Avalanches.

- There is definitely the potential for future landslides around each of the lakes, with the most likely triggers being rainfall and earthquakes. A significant hazard from earthquake induced slope instability exists for most of the slopes around Lakes Lyndon and Coleridge. One particular slope, Peak Hill, is of concern. It has been identified as being affected by some form of gravitational slope movement and if this slope were to collapse during earthquake shaking, it could cause significant waves within the lake, which may threaten opposite low-lying areas (within 10 m elevation of the lake level), such as the Ryton Bay area. Other slopes of concern include the Harper Fan and other subaqueous slopes, which have the potential to collapse and generate tsunami, and the slopes on either side of the Ryton River, which if landsliding were to occur, could dam the Ryton River, therefore, threatening development downstream.

- A significant hazard from earthquake induced slope instability also exists for a few slopes around Lake Tekapo but not to the same extent as around Lakes Lyndon and Coleridge. Currently, the development around the lake is concentrated at its southern end. The main threat to the development in this area comes from Mount John, which appears to have two sections affected by gravitational slope movement. This is of particular concern due to new development occurring at the base of this slope. If failure were to occur, a few million cubic metres of material could potentially be activated. Apart from Mount John, the other major areas of potential slope instability are the north-western mountains and the Godley River delta, all of which are capable of producing waves which could adversely affect the low-lying area of the Richmond freehold area.

CHAPTER 6

CLIMATE HAZARDS

6.1 Introduction

New Zealand's long and narrow form, mountainous terrain and maritime setting, make the country particularly vulnerable to climate hazards (Hicks & Campbell, 1998). Climate hazards occur when the climate conditions of an area depart from normal, to such an extent that people, property and/or social systems are adversely affected (Campbell & Erickson, 1990). Such extreme weather events include high winds, drought, heavy snowfall and heavy rainfall, which can lead to a number of consequences, such as flooding and landslides. Future climate change is most likely going to affect patterns of frequency and magnitudes of such events, leading to a possible increase in climate hazards (ibid). As most natural hazards are influenced either directly or indirectly by climate, the potential effects on lakeside development are of huge concern and are investigated in this chapter.

6.1 The Climate Setting of Canterbury

New Zealand's climate is strongly influenced by the surrounding seas and prevailing westerly circulation of its mid-latitude location (National Institute of Water and Atmospheric Research, 2004). The Southern Alps form an orographic obstacle to the prevailing westerly circulation so the sheltered eastern area of the South Island, including most of Canterbury, is much drier than the exposed western areas (Warrick *et al.*, 2001a) (Figure 6.1). Rainfall varies significantly from west to east, with an annual average rainfall of 10,000 mm in the Alps to 600 to 800 mm in the plains (ibid). Average annual temperatures range from less than 8ºC in the Alps to 10 to 12ºC in the Canterbury Plains (ibid). As a result of its climate setting, Canterbury is subject to high winds, droughts, heavy snowfall and flooding.

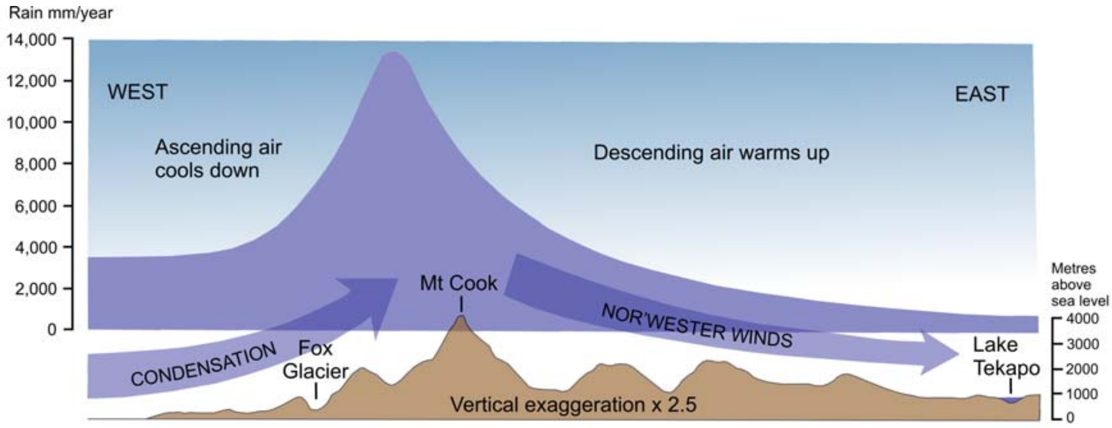

Figure 6.1: Precipitation changes across the Southern Alps into Canterbury. Annual precipitation climbs rapidly to a maximum of c. 13 m west of the Main Divide. After the release of moisture in the west, the airflow descends eastward to become a warm, dry wind - the 'nor'wester'. Modified from Coates (2002): 62.

6.2 Climate Hazards of Lakes Lyndon and Coleridge

Lakes Lyndon and Coleridge have a climate of extremes, with conditions inclined to change rapidly. The area is prone to extremely strong winds, snowstorms and floods. A summary of climate information is provided in Table 6.1 and the following account of the area's climate and related hazards is taken primarily from Britten (2000).

Table 6.1: Summary Climate Information for Lake Coleridge for the 1971 to 2000 period. Source: National Institute of Water and Atmospheric Research (NIWA). Unpublished material.

Rainfall	Wet-days	Sunshine	Temperature			Ground Frost	Wind	Gale days
mm	*≥ 1.0 mm*	*hours*	*Mean ºC*	*Maximum ºC*	*Minimum ºC*	*days*	*Mean speed km/h*	*Mean speed at least 63 km/h*
819.4	91	-	10.6	33.4	-7.8	123	-	-

6.2.1 Wind

The Lake Coleridge area is notorious for its very strong winds, in particular the 'nor'wester', the wind that brings rain to the western side of the Main Divide then warms up as it descends over the alps, turning into a dry, hot and destructive wind

(Figure 6.1). Average and maximum wind speeds have not been obtained for the region but the wind has been described as so strong that people have been reduced to crawling on their hands and knees. This wind, which has not only caused a large amount of structural damage in the past, is also capable of producing relatively large waves on the lakes themselves (more than a metre high). Nor'wester winds also often change dramatically to a south-west wind, which typically brings very cold and wet weather.

6.2.2 Snow

Snow usually falls each winter, with heavy snowfalls occurring every few years. A number of exceptionally heavy snowfalls have occurred in the past, blocking roads, bringing down power and telephone lines, and essentially isolating the area from the rest of the country. Notable snow events occurred in 1867, 1918, 1945, 1967, 1973, 1992 and 2006, with the 1867 event known to be the most destructive. Three days of heavy rain was followed by a week of ongoing snow. Many people were trapped in their houses and reduced to starvation rations. When the weather began to clear and the snow began to melt, widespread flooding occurred, drowning hundreds of sheep that had not already perished in the snow. Many farmers never recovered from their loss during this storm.

6.2.3 Rain

The region does not experience a particularly large amount of rain and has on average 91 wet days per year (Table 6.1). However, prolonged rainfall events do occur now and then, in which the gravelly moraine on the southern side of the lake reportedly becomes "waterlogged and unstable" (Britten, 2000 pg 55). The upper catchments of the major rivers in the area receive a lot more rainfall than the areas around the lakes themselves, and prolonged rainfall or snowmelt into these catchments often causes the rivers to flood. These floods are described as "powerful and dirty, strong enough to roll boulders along the river bed and eat into the bank, endangering man-made structures" (Britten, 2000 pg 55). Most of the rivers around Lake Coleridge are susceptible to flooding (Figure 6.2).

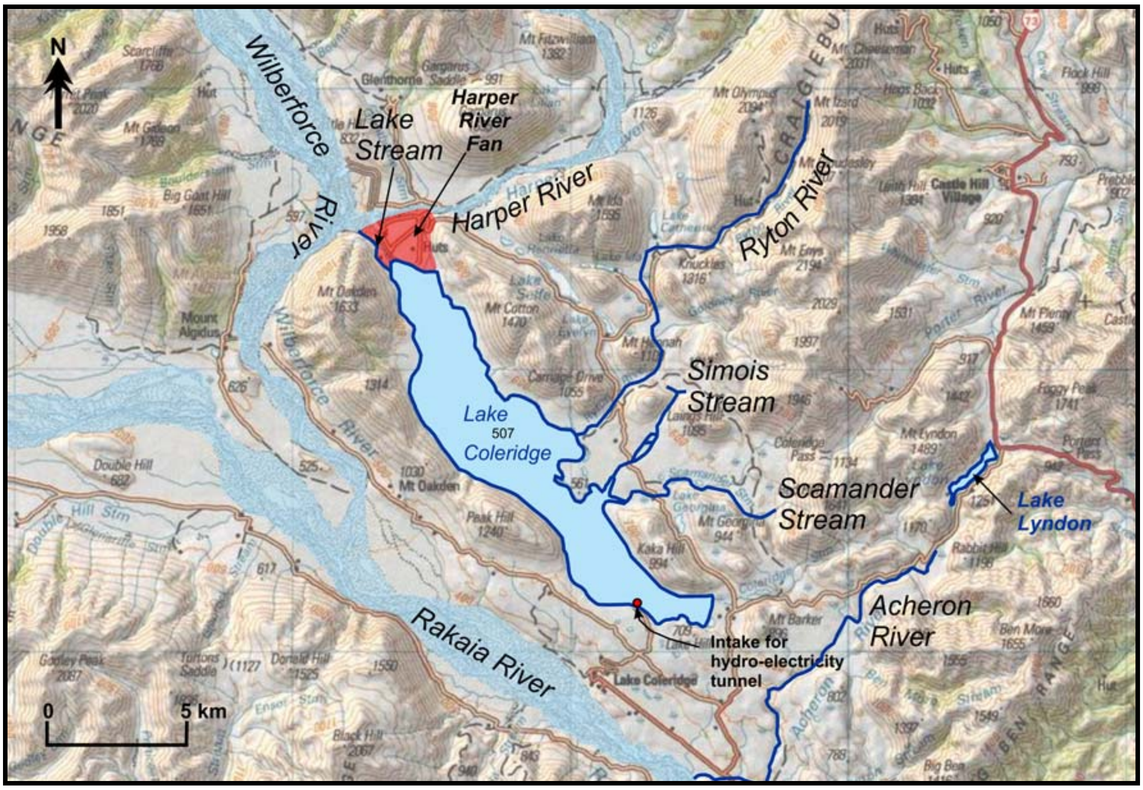

Figure 6.2: The major rivers around Lakes Lyndon and Coleridge.

The Harper and Wilberforce Rivers have been carefully monitored ever since their diversion into the lake. Floods in these rivers have the potential to cause significant damage to diversion control structures and indeed, to any development on the Harper River Fan. The Acheron River, which runs in between Lakes Lyndon and Coleridge, flooded in April 1951 when heavy rain persisted for three days throughout Canterbury. Damage to the area is thought to have been disproportional to its size. The streams entering the north-eastern side of Lake Coleridge are also capable of flooding, but have proved less of a problem in the past than the rivers already mentioned. This is probably due to less development and infrastructure on this side. However, they have been known to flood severely enough to wash out culverts and cause damage to Harper Road. The largest watercourse entering this side is the Ryton River. Before this river was bridged in 1948 it was a real hazard to traffic crossing it. As development pressures increase on the north-eastern side of the lake, the flooding hazard from these rivers, most notably from the Ryton River, increases. Lakeside areas may also be at risk from flooding from fluctuating lake levels. However, the level of the lake is controlled. A maximum level is set at 509.5 m and a minimum level is set at 505.35 m (Hulley, 2004). Therefore, there is a greater risk of flooding from adjacent rivers than there is from a fluctuating lake level.

6.3 Climate Hazards of Lake Tekapo

Lake Tekapo also has a climate of extremes, experiencing warm summers and very cold winters. The mean annual temperature of the Tekapo Township is 8.8ºC. The highest temperature recorded in Tekapo has been 33.3ºC and the lowest recorded has been -15.6ºC (Table 6.2).

Table 6.2: Summary Climate Information for the Lake Tekapo Township for the 1971 to 2000 period. Source: National Institute of Water and Atmospheric Research (NIWA). Unpublished material.

Rainfall	Wet-days	Sunshine	Temperature			Ground Frost	Wind	Gale days
mm	*≥ 1.0 mm*	*hours*	*Mean ºC*	*Maximum ºC*	*Minimum ºC*	*days*	*Mean speed km/h*	*Mean speed at least 63 km/h*
600	78	2180	8.8	33.3	-15.6	149	7	1

6.3.1 Wind

The prevailing wind at Lake Tekapo is a north-easterly,, but like anywhere in Canterbury, the region is also susceptible to strong north-west winds (Owen, 1993). The average wind speed at Tekapo is 7 km per hour but warm gusty winds often exceed 8 to 14 km per hour (McGowan & Sturman, 1997). Strong north-west winds can occur in any month and have the ability to accentuate drought, which often affects the area (Owen, 1993). On average, the township area experiences one gale day per year in which the average wind speed exceeds 63 km per hour (Table 6.2). In fact, the highest wind speed ever recorded in New Zealand (250 km per hour) was recorded on top of Mt John. The region is also susceptible to strong south-west winds, which typically bring very cold and wet weather.

6.3.2 Drought

The Lake Tekapo region is also susceptible to droughts, which can have a devastating impact on the area. Farming communities are usually hit the hardest, with stock numbers often completely collapsing. As mentioned previously, strong nor'westerly winds can accentuate drought as they tend to withdraw any remaining water from the land (Hicks & Campbell, 1998). One of the most notable effects of a drought in the region is a low lake level, which has a huge effect on the New Zealand economy, raising power prices and restricting electricity usage. Droughts are often followed by severe floods (ibid).

6.3.3 Snow

During winter, Lake Tekapo receives a substantial amount of snow. Falls of 50 to 70 cm may be experienced at lake level, while numerous lighter falls may also occur (McGowan & Sturman, 1997). The area also experiences, on average, 149 ground frost days. Heavy snowfalls occasionally cause disruptions to telephones, power supply and road traffic. They often cause structural damage to buildings and occasionally cause buildings, such as hay barns, to collapse. Heavy snowfalls can also isolate townships in the Lake Tekapo area for several days.

6.3.4 Rain

On average, the Tekapo Township only experiences 78 wet days per year (>1 mm of rain) (Table 6.2), which produces an annual rainfall of 600 mm. However, the amount of rain significantly increases towards the Main Divide at the head of the lake. Annual rainfall can exceed 5000 mm at the headwaters of the lake catchment (McGowan & Sturman, 1997). Mean monthly inflows into Lake Tekapo are the highest during the spring to summer melt (December to January) (Irwin & Pickrill, 1982) and as a result, the lower reaches of all the rivers are prone to flooding (New Zealand Department of Lands and Survey, 1980) (Figure 6.3). For example, the delta of the Godley River is almost always flooded during summer (Graham *et al.*, 2005). The lower reaches of the

Cass River are also particularly vulnerable to flooding. At the road bridge, the river is very unstable and it can often take a week to clear after heavy rain (Kent, 1998).

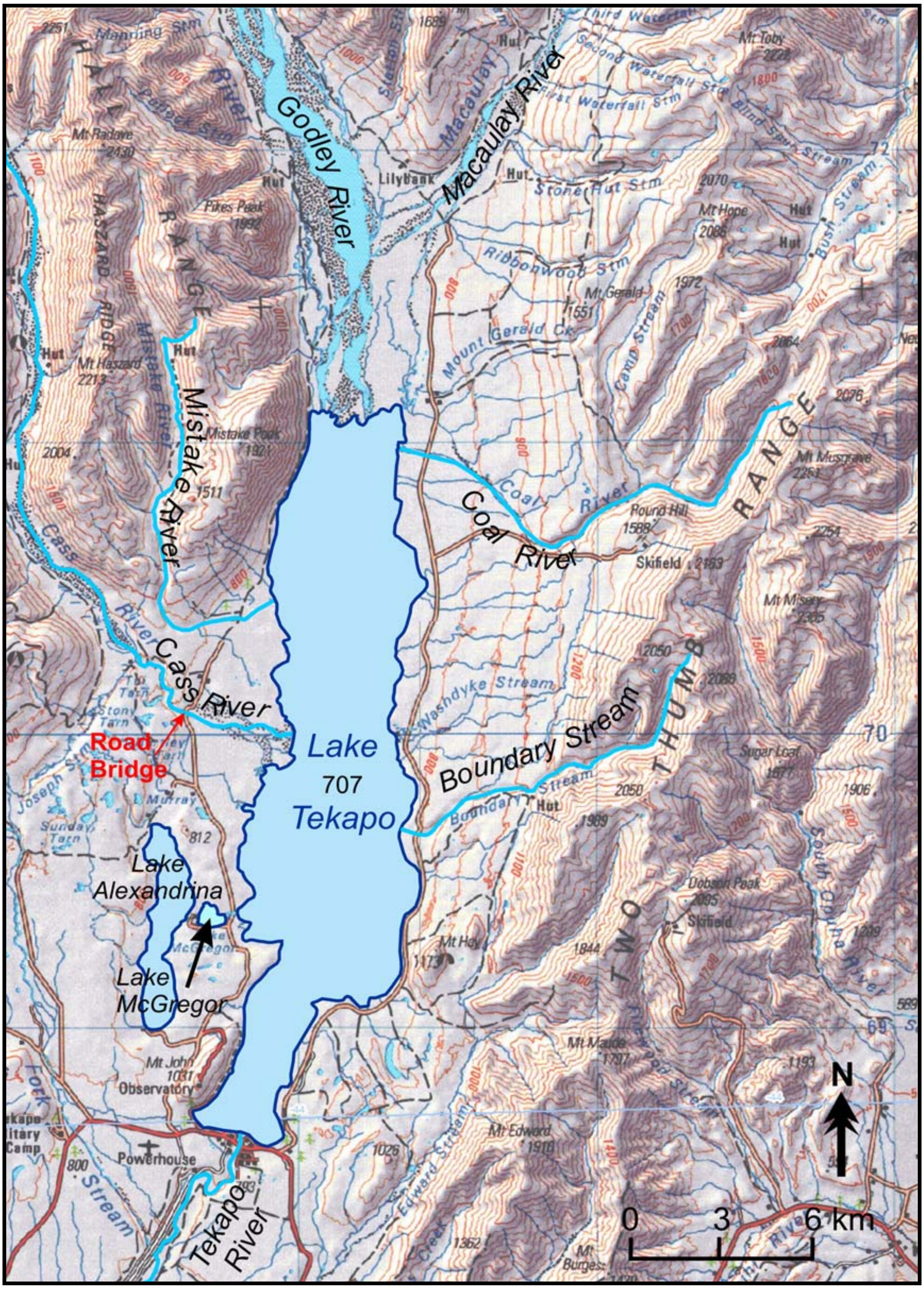

Figure 6.3: Major rivers around Lake Tekapo.

Lakeside areas are not only at risk from flooding from adjacent rivers, but are also at risk from flooding due to fluctuating lake levels. Different maximum lake levels are set for different months of the year and this, along with the amount of spring and summer melt, determines the lake level (New Zealand Department of Lands and Survey, 1980). Lake Tekapo has a 9 m operating range and a lower limit of 702.1 m. The upper limit varies on a month-to-month basis, from 709.7 m to 710.9 m. Tekapo residents and holidaymakers prefer the lake to remain above 707 m during the summer period for recreational and aesthetic reasons. However, if the lake levels remain high, there is a potentially higher flood risk as the storage buffer is decreased.

6.4 Climate Change

Climate is the typical range of weather, including its variability, that a particular region experiences (Barrie Pittock, 2005). It is usually based on average weather conditions over approximately 30 years. A change in weather behaviour over a longer time period, such as centuries or millennia, is referred to as ‘climate change’ (ibid). Globally and locally, climate has changed vastly over geological time scales. For example, Figure 6.4 shows global variations in carbon dioxide (CO_2) and temperature over the past 350,000 years. Climate change is caused by dynamic natural processes on earth, external forces, such as variations in sunlight intensity, and more recently by human activities. It is evident from Figure 6.4 that, overall, temperatures have generally been increasing for the last c. 20,000 years. However, what is of immediate concern is that within the last few decades alone, there has been an almost unprecedented rapid global warming trend (Barrie Pittock, 2005). CO_2 concentrations have also risen at an alarming rate of 35 per cent since 1750, and are currently at a level not experienced over the last 650,000 years (O'Donnell, 2007).

It is now generally accepted that human activities have accelerated climate change over the last few centuries, most notably from the beginning of the industrial revolution in the late 18th century. The recent warming has been induced primarily by changes in the composition of the earth’s atmosphere, notably from the release of greenhouse gases, such as carbon dioxide, methane and oxides of nitrogen (Barrie Pittock, 2005).

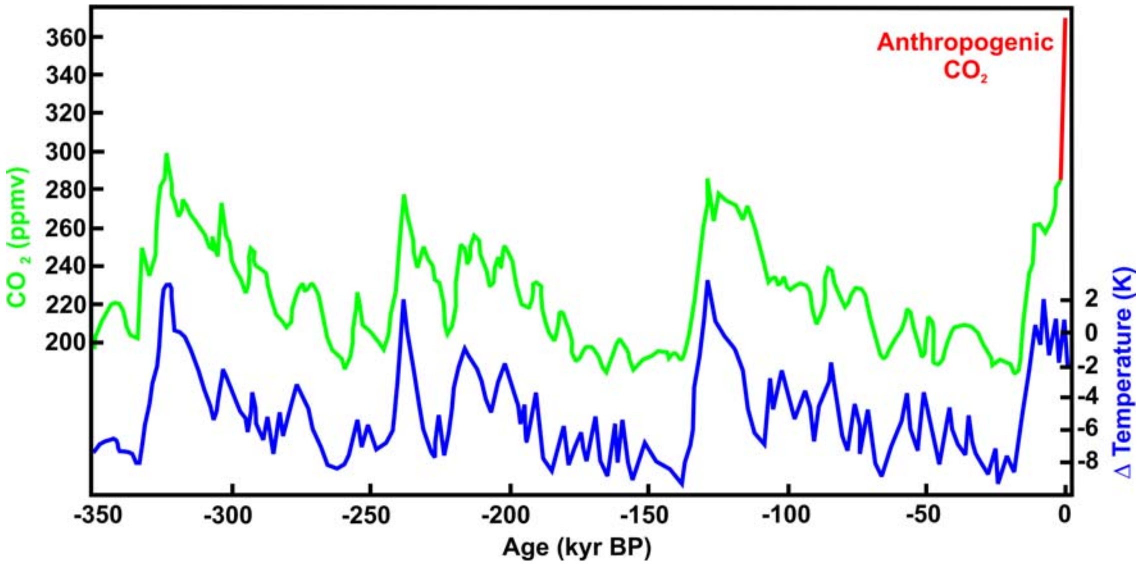

Figure 6.4: Records of CO_2 (green) and temperature (blue) over the past 350,000 years from the Vostok ice core. The recent anthropogenic rise in CO_2 is marked in red. Source O'Donnell (2007): 7.

These gases absorb heat radiation from the sun or Earth and when warmed, produce heat radiation both upwards into space and downwards to Earth (ibid). They, therefore, act like a blanket around the earth trapping heat. Human activities have significantly increased the concentration of several greenhouse gases, mainly from the burning of fossil fuels, including coal, oil and natural gas, through the destruction of forests and carbon-rich soil, and from the manufacture of cement from limestone (ibid). Changes in land surface reflectivity caused by land clearing, cropping and irrigation have also induced changes to the composition of the atmosphere (ibid).

Climate change due to global warming is likely to have major and potentially irreversible effects, at global and local scales, on both the environment and human lives. Effects of recent climate change include rising sea levels, glacier retreat and Arctic ice shrinkage. The majority of further consequences will arise from higher local temperatures, changes in rainfall patterns and from sea level rise. What this means for climate hazards within Canterbury and more specifically to lakeside areas around Lakes Lyndon, Coleridge and Tekapo is now explored.

6.5 Natural climate variations in New Zealand

Irrespective of increases in greenhouse gas emissions, New Zealand's climate continually changes (Warrick *et al.*, 2001b). This is mainly due to natural variations in climate, which are related to the atmospheric circulation around New Zealand and the consequent variations in the airflow direction (ibid). There are two main climate variations that affect New Zealand – the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (O'Donnell, 2007). The ENSO, which comprises El Niño and La Niña, occurs on a time scale of one to three years, and the IPO changes between negative and positive phases on average every two decades (Warrick *et al.*, 2001b). Generally, a more westerly and south-westerly airflow (as during El Niño and positive phases of the IPO) brings cooler temperatures to New Zealand, with an increase in precipitation to the north and east (ibid). The reverse occurs with a more easterly and north-easterly airflow (ibid). A summary of these generalised effects is provided in Table 6.3. Therefore, even though New Zealand expects to experience an overall temperature increase along with the rest of the world, there are sure to be significant variations in this general trend due to the IPO and ENSO.

Table 6.3: Sources of natural variations in New Zealand's climate and their general affects on climate. Source: Warrick *et al*, (2001b): 5.

Interdecadal Pacific Oscillation (IPO)			
Time Period	**Phase**	**Increased Circulation/Airflow from:**	**General Climate Effect on New Zealand**
1922 - 1945	Positive	South to south-west	Generally cooler with drier conditions especially in the north and east.
1946 - 1977	Negative	East to north-east	Generally warmer with wetter conditions especially in the north and east.
1978 - 1998	Positive	West to south-west	Generally cooler with drier conditions especially in the north and east.
El Niño Southern Oscillation (ENSO)			
El Niño		West to south-west	Generally cooler with drier conditions especially in the north and east.
La Niña		East to north-east	Generally warmer with wetter conditions especially in the north and east.

6.6 Projected climate change for New Zealand

Temperature changes within New Zealand are not likely to be as extreme as the global average, due to New Zealand being buffered by surrounding oceans (O'Donnell, 2007). If no steps are taken to reduce greenhouse gas emissions, global average temperatures are expected to rise by c. 3.0°C by 2080 relative to the 1980 to 1999 average (ibid). Under the same scenario, New Zealand’s temperature is expected to rise by c. 1.5°C to 2.0°C. Despite this lower increase, a large variety of future changes are predicted for the country. These are summed up, along with their levels of confidence in Table 6.4.

Table 6.4: Projected Climate Changes for New Zealand. Source: O'Donnell (2007): 15.

Projected climate changes for New Zealand	Level of confidence in the projections
• An increase in average temperature of 0.5-0.7°C by 2030, • and 1.5-2.0°C by the 2080s.	Very high Medium
• Fewer cold temperatures.	Very high
• More high temperature episodes.	Very high
• Changes to average rainfall patterns with substantial variation across the country in keeping with a stronger west-east rainfall gradient.	Medium
• Reduced snow cover, shorter seasonal snow lying, snowline rise, glacier retreat.	Medium
• Heavier and/or more frequent extreme rainfall (especially for areas that are projected to have an increase in average rainfall)	Medium Low
• Increase in the average westerly windflow across New Zealand	Medium
• Increase in severe wind, with little change up to double the frequency of winds over 30m/s by 2080.	Low
• Increase in stormy conditions	Low
• Sea level rise • 30-50 cm sea level rise between 1990 and 2100	Very High High
• Increase in heavy swells in areas exposed to prevailing westerlies (However, the wave climate for Canterbury will continue to be dominated by southerly swells).	Medium

6.7 Projected climate change for Canterbury

Projected climate changes for Canterbury are most likely to mirror those predicted for New Zealand as a whole. However, there are likely to be variations within these predictions. Information for this section has been obtained from Environment Canterbury's climate change report by O'Donnell (2007) unless otherwise stated. This section is split into temperature and rainfall changes.

6.7.1 Temperature changes

Average temperature changes for Canterbury relative to 1990 are provided in Table 6.5. The greatest warming is expected during the winter months, with northern parts of Canterbury projected to warm slightly more than southern areas. A slight cooling may be experienced during summer months due to natural variability caused by the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (refer to section 6.5). Although mean temperatures may only increase by a few degrees, any change at the extreme end of the range of weather experienced, is highly significant (Figure 6.5). Records indicate that Canterbury will experience a significant decrease in the number of frost days and an increase in the number of days exceeding 25°C. This has great implications for potential drought in the region.

Table 6.5: Projected changes in mean temperature (°C) for Canterbury. Source: O'Donnell (2007): 17.

	Summer	Autumn	Winter	Spring	Annual
1990 – 2030s	-0.2 to 1.3	0.1 to 1.1	0.3 to 1.8	0.0 to 1.3	0.2 to 1.4
1990 – 2080s	0.0 to 3.3	0.4 to 3.5	0.8 to 3.9	0.3 to 3.1	0.5 to 3.4

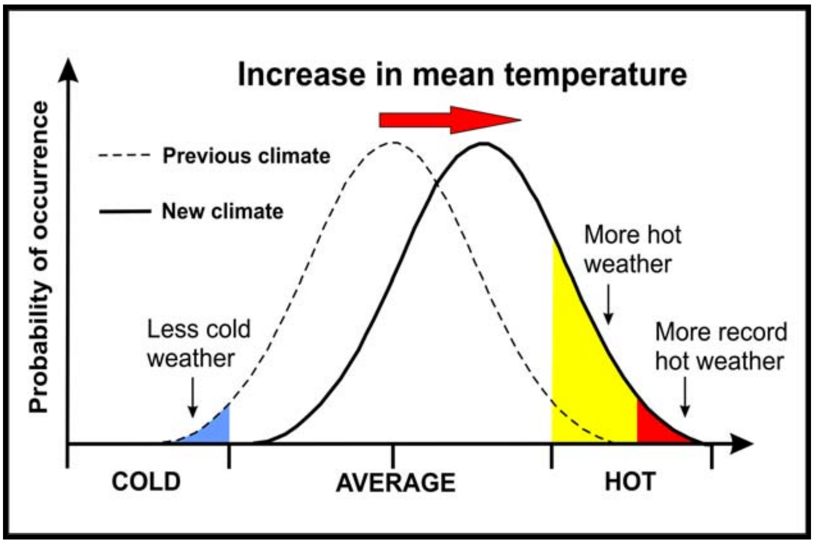

Figure 6.5: Illustrative diagram of the effect of climate change on mean and extreme temperatures. Modified from: O'Donnell (2007): 20.

6.7.2 Rainfall changes

As a warmer atmosphere can hold more moisture, there is potential for heavier and more frequent rainfall for parts of Canterbury. The National Institute of Water and Atmospheric research (NIWA) has developed a number of scenarios for rainfall changes for New Zealand based on global scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). The lowest, middle and highest case scenarios for the Canterbury Region are provided in Figure 6.6. These show the projected changes in annual precipitation for the 2030s and 2080s relative to 1990. It must be noted that there is a level of uncertainty related to each scenario.

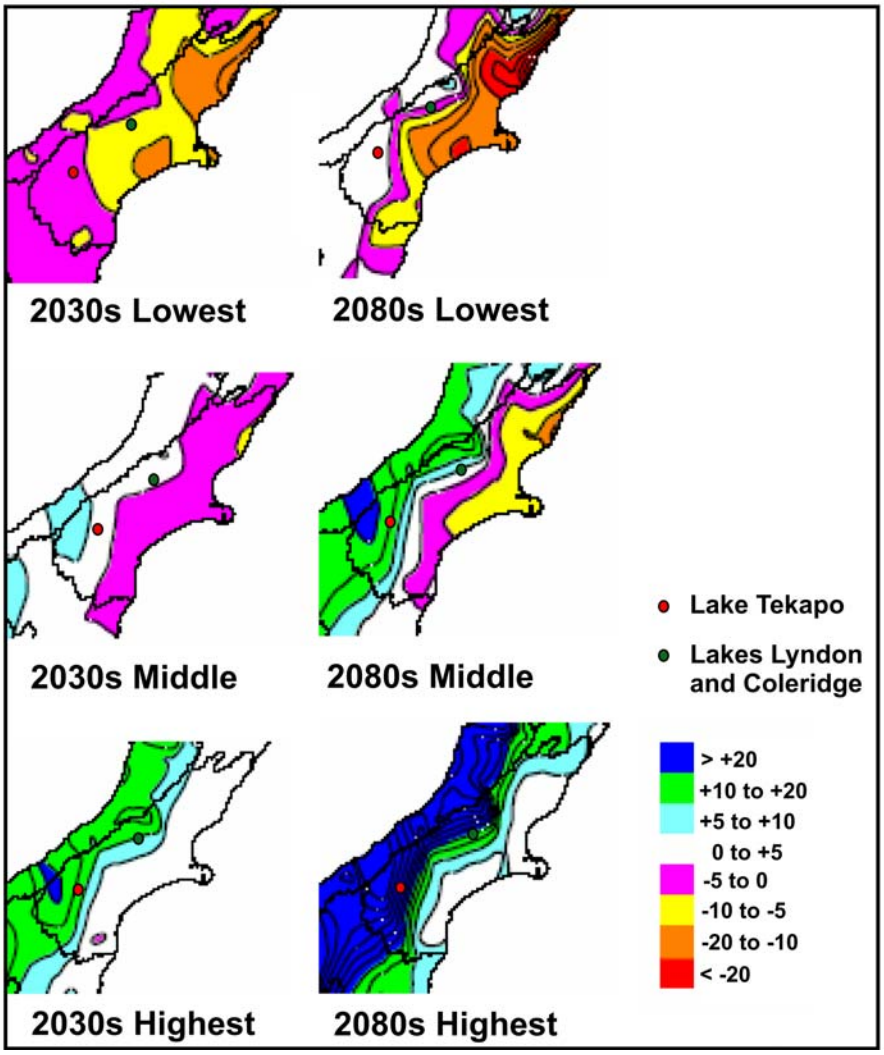

Figure 6.6: Projected annual precipitation change (in %) for the Canterbury Region relative to 1990. The approximate positions of Lakes Coleridge and Tekapo are shown in green and red respectively. Modified from O'Donnell (2007): 18.

Overall projections suggest that the Canterbury ranges will experience an increase in rainfall while the plains will expect a decrease. Therefore, some major eastern rivers with catchments that reach back into the Main Divide, such as the major tributaries of Lake Tekapo (the Godley, Macaulay and Cass Rivers), may experience an increase in their flows. The lowest change scenario in Figure 6.6 depicts a possible decrease in precipitation for the Lakes Lyndon, Coleridge and Tekapo for the period 1990 – 2030s. However, the middle and highest change scenarios indicate that the lakes will most likely experience an increase in precipitation for the same period, of between 0 and 20 per cent. Between 1990 and 2080, the lowest change scenario suggests that Lakes Lyndon and Coleridge may experience a decrease in precipitation between –10 to 0 per cent. However, middle and high change scenarios suggest that these two lakes will receive an increase in rainfall of 0 to >20 per cent. For the same period, Lake Tekapo is expected to experience a rainfall increase of 0 to >20 per cent. There is, therefore, a high level of variability in possible rainfall changes associated with each lake. However, it is worth considering the worst-case scenario. It is also apparent that seasonal variations will occur. An increase in rainfall and of the frequency and magnitude of extreme rainfall events is the most important result of climate change with respect to natural hazards (Campbell & Erickson, 1990). This is because rainfall strongly influences river flooding, land instability, and drought (ibid).

6.7.2.1 Floods and Storms

An increase in the magnitude and frequency of rainfall events will lead to an increase in the magnitude and frequency of floods, which is of particular significance to lakeside properties (Campbell & Erickson, 1990). Areas previously considered relatively safe from flooding may become more at risk and the vulnerability of development, which is located on floodplains or next to shorelines, may increase (ibid). Climate change is also projected to bring about more frequent and intense storms in Canterbury. A storm, such as a tropical cyclone, is a multifaceted event consisting of extreme wind, sea and rainfall events (Campbell & Erickson, 1990). Winds associated with such events can be extremely strong and have the potential to cause significant damage to structures both directly and indirectly. High waves, which can be generated by such winds, can cause shoreline erosion and flooding (ibid).

6.7.2.1.1 Potential lakeside development areas most susceptible to floods and storm waves around Lake Lyndon

As most of the land to the south of Lake Lyndon is within 10 m elevation of the lake, this area is susceptible to flooding and storm waves (Figure 6.7). Lyndon Road, which runs immediately east of the lake, is also susceptible to storm waves and flooding.

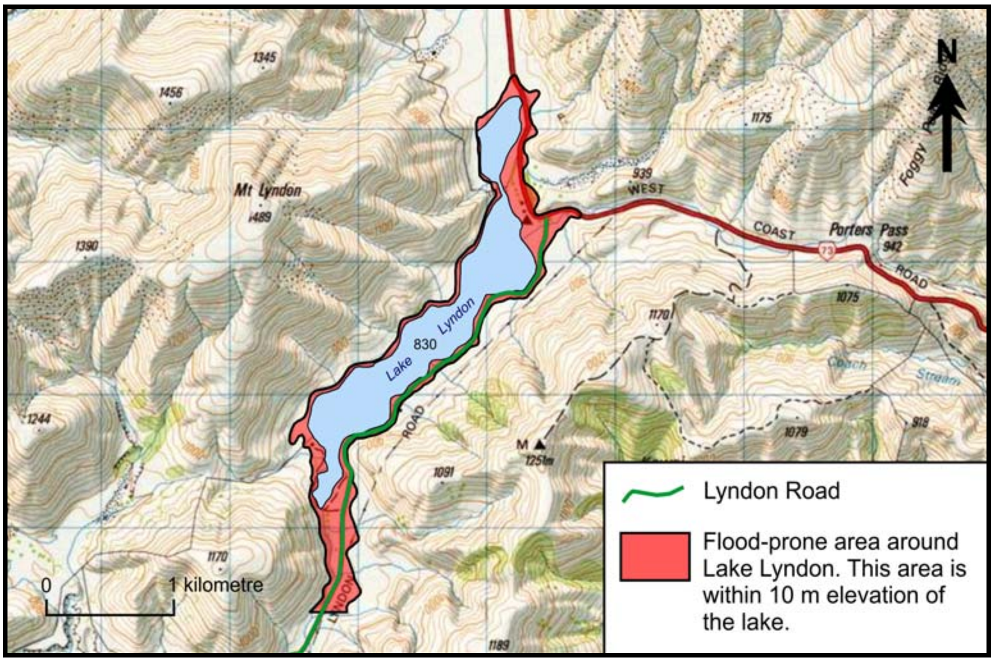

Figure 6.7: The area around Lake Lyndon, which is most susceptible to flooding.

6.7.2.1.2 Potential lakeside development areas most susceptible to floods and storm waves around Lake Coleridge

If water levels at Lake Coleridge were to increase significantly, a limited amount of water could be released through the hydro-electricity intake tunnels. However, low-lying areas around the lake would still be at significant risk from flooding and storm waves. Areas of potential development most at risk include the Harper Fan area (Figure 6.8), the floodplain of the Ryton River (Figure 6.9) and low-lying areas around Coleridge Station (Figure 6.10).

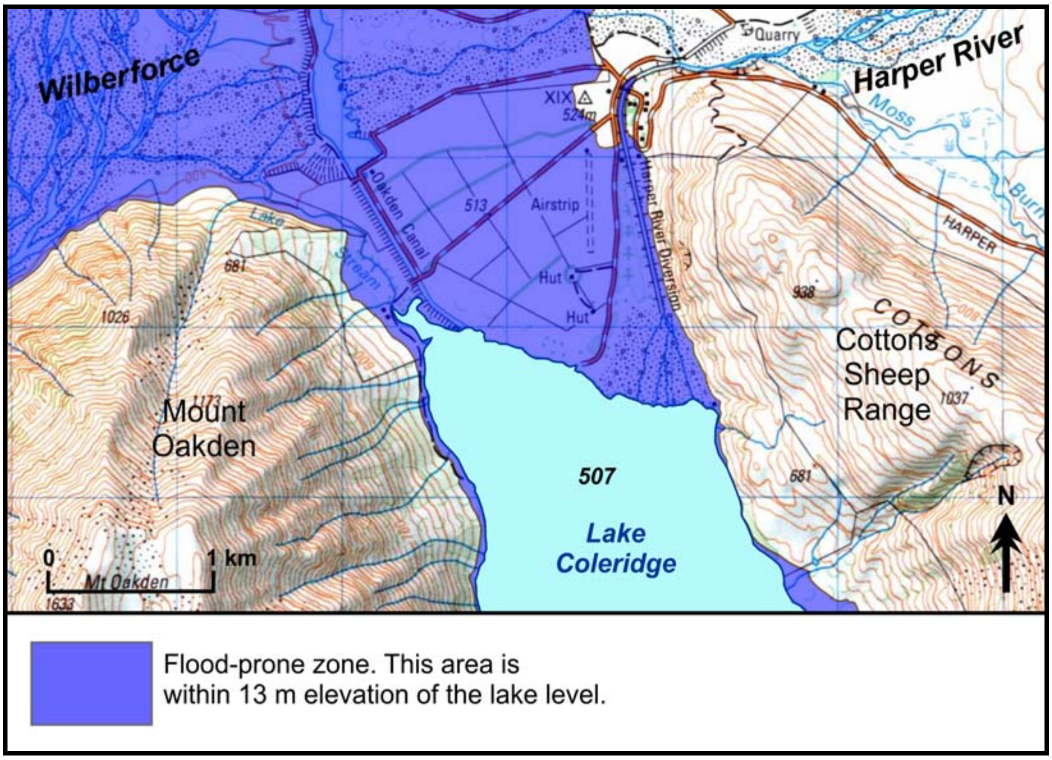

Figure 6.8: The low-lying, flood-prone zone of the Harper Fan.

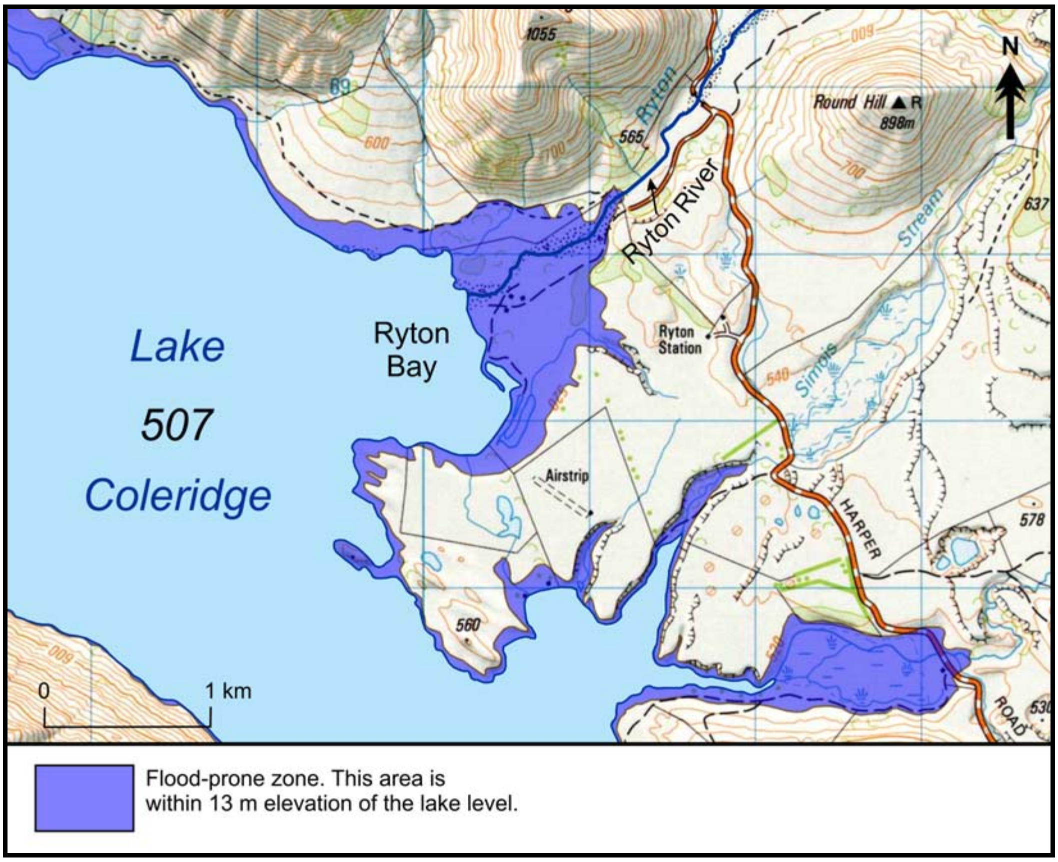

Figure 6.9: The low-lying, flood-prone zone of the north-eastern side of Lake Coleridge.

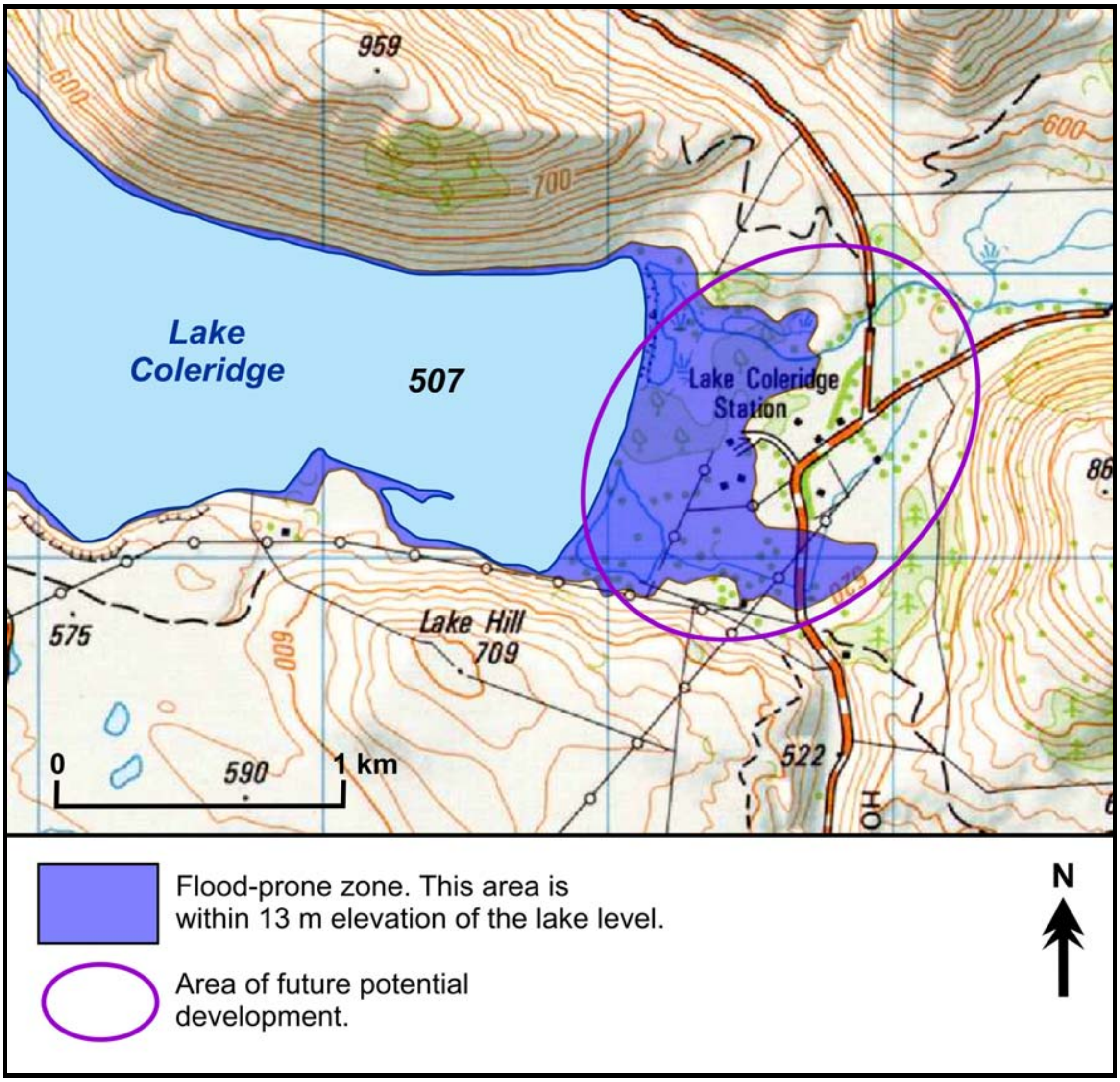

Figure 6.10: The low-lying, flood-prone zone surrounding Lake Coleridge Station.

6.7.2.1.3 Potential lakeside development areas most susceptible to floods and storm waves around Lake Tekapo

If lake levels at Lake Tekapo were to increase significantly, a lot of water could be released through the control gates into the Tekapo River. However, this may not always be possible due to potential flooding risks downstream. Low-lying areas at risk from storm waves and flooding include the coastal areas of the Richmond freehold area and the floodplain of Coal River (Figure 6.11), and a significant portion of the Tekapo Township, at the lake's southern end (Figure 6.12).

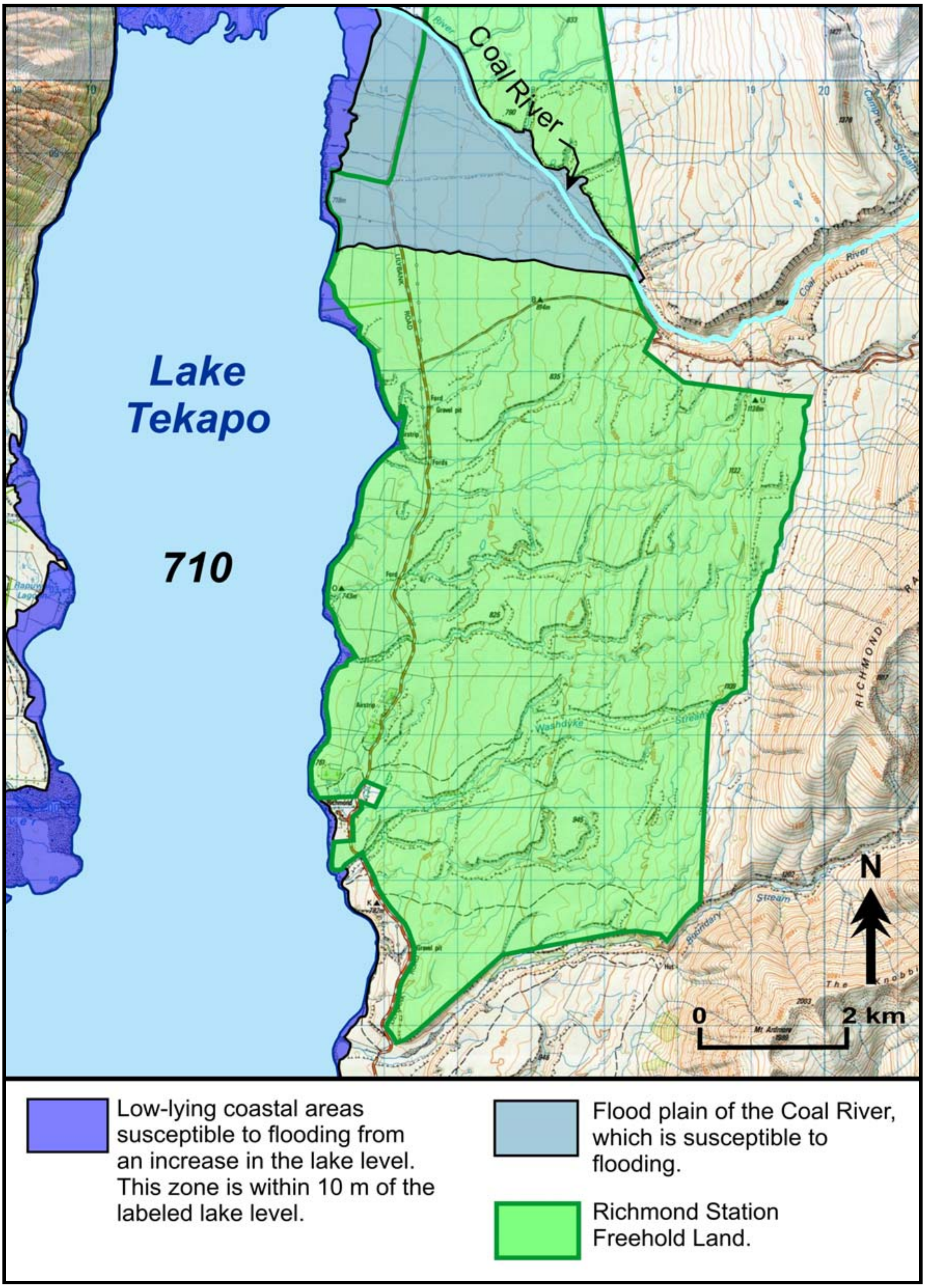

Figure 6.11: The flood-prone areas of the Richmond Station Freehold Land. Note that this area is prone to flooding from fluctuating lake levels and from the Coal River.

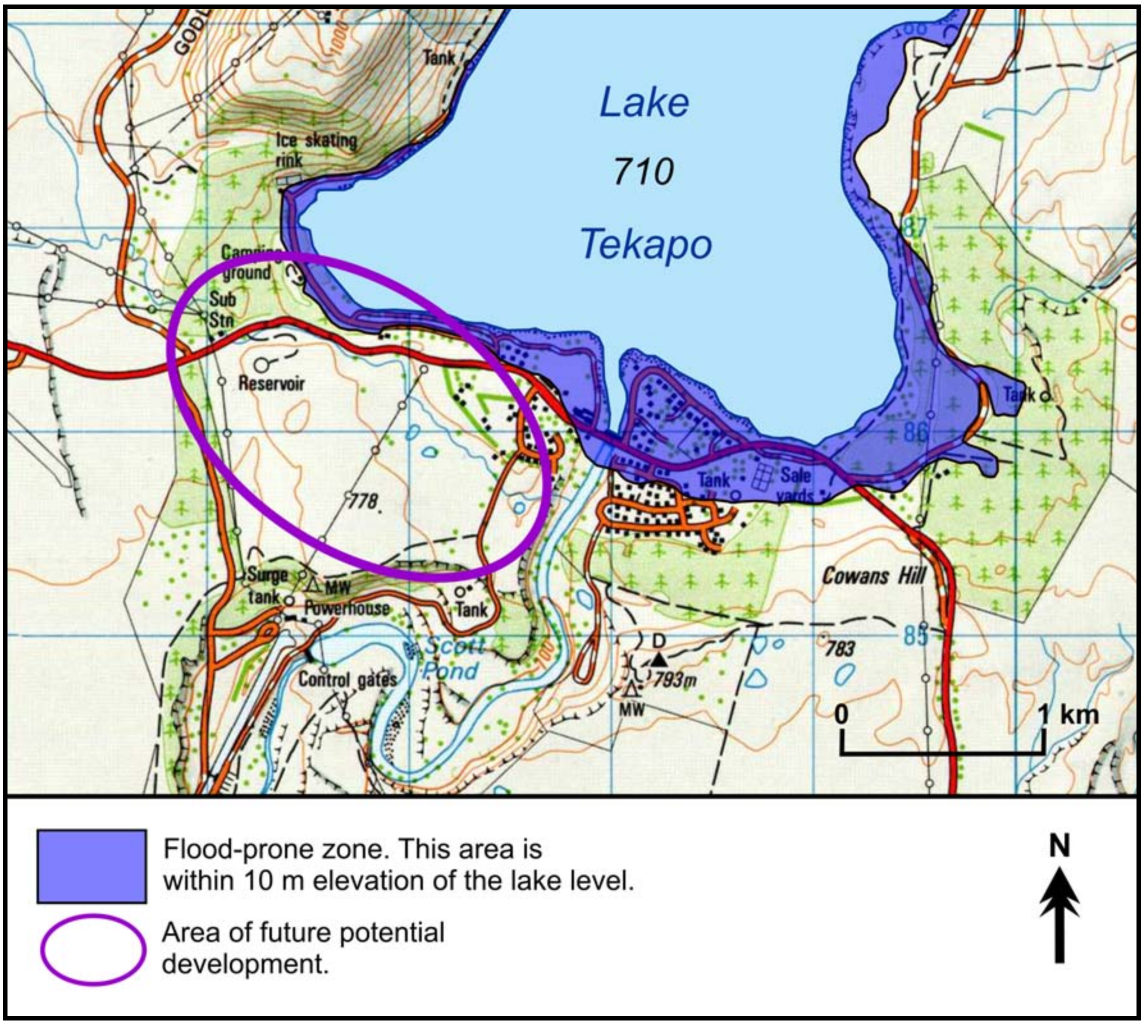

Figure 6.12: The low-lying, flood-prone areas around the Tekapo Township.

6.7.2.2 Slope instability

As extreme rainfall events are a major cause of landslides, an increase in the frequency and magnitude of landslides will also most likely occur within the Canterbury Ranges. Refer to chapter 5 for lakeside areas most susceptible to slope instability.

6.8 Dealing with Climate Change

As recognised by O'Donnell (2007), there are two main aspects to dealing with climate change. Firstly, in order to reduce anthropogenic causes of climate change as much as possible, greenhouse gas emissions must be reduced. New Zealand has recognised this need and is part of the international effort to do so. Secondly, as future climate change is inevitable, we must learn to adapt to likely effects. Through adaptation, there is the potential to reduce adverse effects of climate change and to enhance beneficial effects. However, in order to adapt, people must be made aware of likely changes that will occur. There is a lot of information available in New Zealand and climate change issues are being recognised by the government. With respect to lakeside development, developers and consent givers must take into consideration how climate change is likely to affect particular areas. In terms of lakeside areas, which expect an increase in the magnitude and frequency of rainfall and storms, avoidance of landslide and flood prone areas should be top priority.

6.9 Chapter Summary

- New Zealand's long and narrow form, mountainous terrain and maritime setting, make the country particularly vulnerable to climate hazards. Canterbury is subject to extreme weather events, including high winds, drought, heavy snowfall and heavy rainfall, which can lead to a number of effects, such as flooding and landslides. Consequences of climate hazards include death and injury to people and livestock, structural damage to infrastructure and lifelines, and isolation of regions.

- Lakes Lyndon and Coleridge have a climate of extremes, with conditions inclined to change rapidly. The area is prone to extremely strong winds, snowstorms and floods. Lake Tekapo also has a climate of extremes and is prone to high winds, heavy snowfall, heavy rainfall, droughts and flooding.

- Globally and locally, climate has changed vastly over geological time-scales. Temperatures have been increasing for the last c. 20,000 years and what is of immediate concern is that within the last few decades alone, there has been an almost unprecedented rapid global warming trend. Climate change due to global warming is likely to have major and potentially irreversible effects at global and local scales on both the environment and human lives. Future climate change is most likely going to affect patterns of frequency and magnitudes of extreme weather events, leading to an increase in climate hazards. As most natural hazards are influenced either directly or indirectly by climate, the potential effects on lakeside development are of huge concern.

- Projected climate changes for Canterbury include:
    1. An increase in temperature of between 0.5 to 3.4ºC by the 2080s relative to 1990,
    2. Fewer cold temperatures,
    3. More high temperature episodes,
    4. An increase in rainfall in the Canterbury Ranges and a decrease in the plains,
    5. Heavier and more frequent rainfall for areas projected to have an increase in average rainfall (i.e. the Canterbury Ranges),
    6. Reduced snow cover, shorter seasonal snow lying, snowline rise and glacier retreat,
    7. An increase in severe wind, and
    8. Increased stormy conditions.

- An increase in the magnitude and frequency of rainfall events in the Canterbury Ranges will lead to an increase in the magnitude and frequency of floods, which is of particular significance to lakeside properties. Areas previously considered relatively safe from flooding may become more at risk and the vulnerability of development, which is located on floodplains or next to coastlines, may increase. As extreme rainfall events are a major cause of landslides, an increase in the frequency and magnitude of landslides will also most likely occur within the lake areas. Therefore, the areas around the lakes most susceptible to climate hazards and their consequences, are low-lying areas next to the lakes or rivers and also areas next to landslide-prone slopes.

CHAPTER 7 -
SUMMARY AND CONCLUSIONS

7.1 Introduction

Lakes Lyndon, Coleridge and Tekapo are all, in part, susceptible to earthquake, landslide and climate hazards. As these lakes become more developed, the potential consequences from these hazards increases. It is paramount that all parties involved in the development process are aware of these hazards, so that they can be avoided if necessary. This reconnaissance study has identified areas with the most potential for development and has identified the natural hazards specific to these areas.

7.2 Areas of potential future development

In this study, the areas around the lakes which have a high possibility of being intensely developed, have been of interest. These areas are not only a function of the natural environment (i.e. suitable topography) but also of the social environment (i.e. land ownership). The land around the lakes is generally divided into Crown-owned pastoral lease, conservation land (also Crown-owned) and privately owned freehold land. Land ownership defines what can and cannot be done on that land. For example, there are restrictions on the level of development allowed on Crown-owned land. Pastoral leases can generally only be used for pastoral purposes and it is very unlikely that much other development would be allowed. Any development on conservation land must be tied in closely with conservation or recreation purposes. With freehold land, owners can diversify into economic activities, such as subdivision and ecotourism, giving this land the most potential for intense development. Therefore, taking into consideration both natural and social factors, the areas deemed most likely to have development occur on them were examined.

7.2.1 Lake Lyndon

Approximately half of the land around Lake Lyndon is part of the Korowai/Torlesse Tussocklands Park, which is protected conservation land (Figure 7.1). The other half of land surrounding the lake is part of the Brooksdale pastoral lease owned by the Crown. Therefore, based on land ownership around the lake, there is not a lot of potential for development to occur. However, there is the possibility that Brooksdale lease could go through the Tenure Review and part of the land could become freehold. However, preliminary work suggests that the area around the lake would be retained by the Crown and subsequently protected from development, such as subdivision.

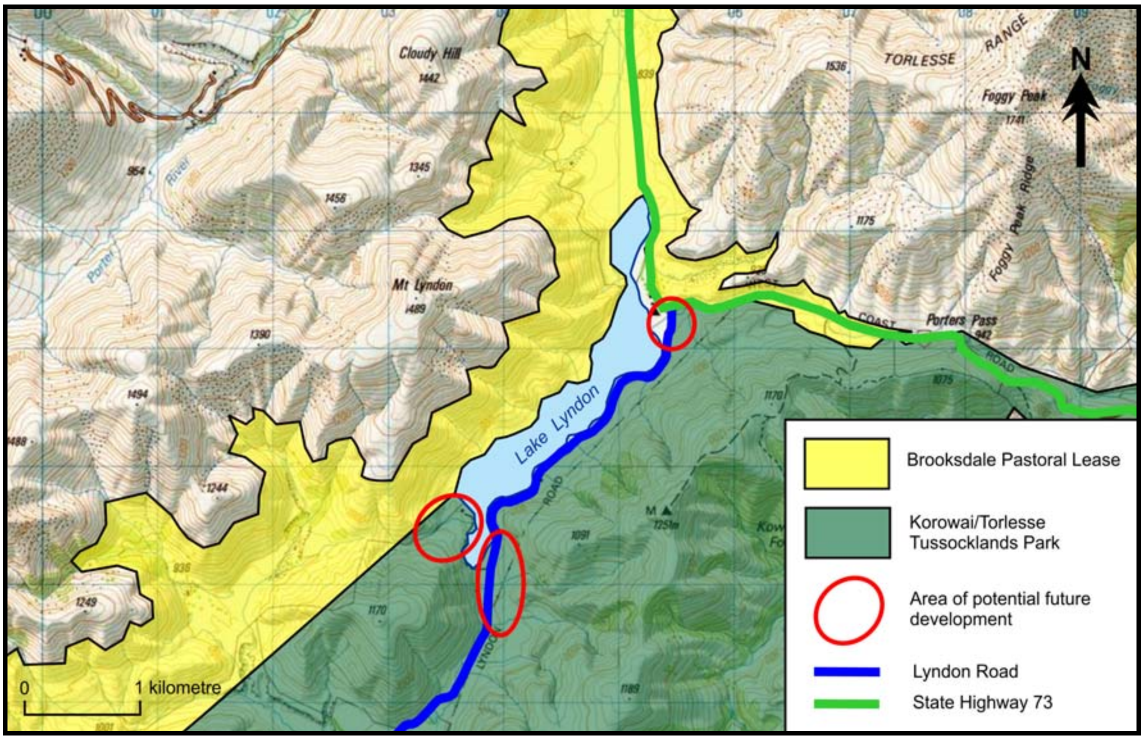

Figure 7.1: Land allocation and the most likely areas for future development around Lake Lyndon. Land allocation boundaries are approximate only.

The most likely sites for development, based on natural topography, occur at the lake's northern and southern ends where there are a few open flat areas. However, these areas are Department of Conservation (DoC) land and it is unlikely that much development would be allowed. Nevertheless, there is a possibility that some form of development linked with conservation or recreation purposes could occur.

7.2.2 Lake Coleridge

There is more potential for development around Lake Coleridge than at Lake Lyndon. Most of the land surrounding the lake is privately owned and has potential for future development. The rest of the land is Crown-owned (Figure 7.2). Mount Oakden pastoral lease was recently included among the 65 lakeside properties protected from over-development by the government. Therefore, this area will most likely continue to be used for pastoral purposes. A large part of Peak Hill recently became freehold and as a result, has potential for future development. However the lakeside part of this land is not suitable for development due to steep topography and has not been considered in this study. Therefore, taking into account freehold areas with suitable flat-lying topography, the most likely sites for future development at Lake Coleridge include,

1. The Harper fan area to the north of Lake Coleridge,
2. The north-eastern area between Carriage Drive and Kaka Hill,
3. The area surrounding Coleridge Station at the lake's eastern-most end, and
4. The area to the south of Lake Coleridge between Peak Hill and Lake Hill.

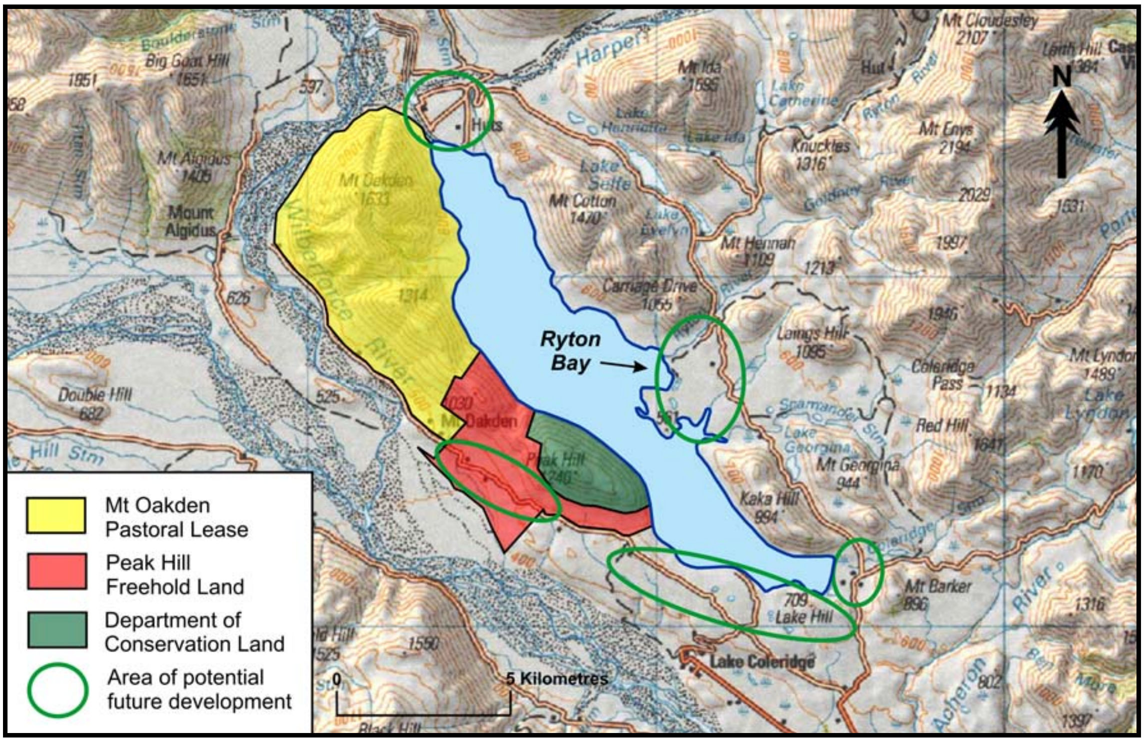

Figure 7.2: Land allocation and the most likely areas for future development around Lake Coleridge. Land allocation boundaries are approximate only.

7.2.3 Lake Tekapo

There is also potential for development around Lake Tekapo, but within quite restricted areas. This is because most of the land around the lake is divided into pastoral leases (Figure 7.3). Balmoral, Glenmore Station, Godley Peaks, Mount Gerald, Mount Hay and Sawdon are among 65 properties now protected from development, such as subdivision, and will most likely continue to be used for farming purposes. One of the leases, Richmond Station completed the Tenure Review process before the government called a halt to Tenure Review of lakeside properties. There is, therefore, huge potential for its freehold land to be developed. A small amount of conservation land lies to the south-east of the lake, which is protected for conservation purposes. The rest of the land to the south and south-west of the lake appears to be privately owned and also has potential for future development. Therefore, there are development prospects for

1. The freehold section of Richmond Station,
2. The privately owned land west of the Tekapo Township, and
3. The coastal area north of Mount John.

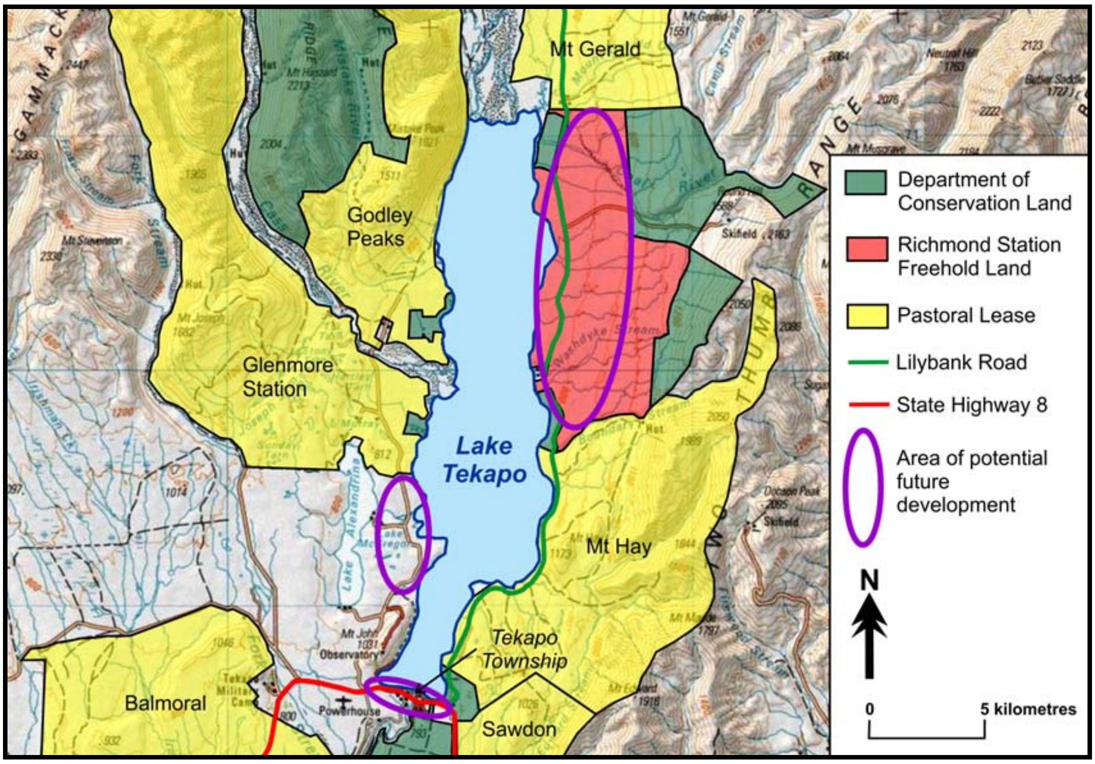

Figure 7.3: Land allocation and the most likely areas for future development around Lake Tekapo. Land allocation boundaries are approximate only.

7.3 An Overview of Natural Hazards at Lakes Lyndon, Coleridge and Tekapo

7.3.1 Earthquakes

Lakes Lyndon, Coleridge and Tekapo are situated within a zone of active earth deformation, characterised by crustal thickening, uplift and faulting (Pettinga *et al.*, 2001). Large and relatively frequent earthquakes are produced within this zone. Significant damage to the lake areas can occur from low to moderate magnitude events from near field faults, or from medium to large faults located up to 100 km from the lakes.

A large number of faults have been identified in the Lakes Lyndon and Coleridge area (Figure 7.4). A handful of these faults have been studied extensively, and their seismic properties, such as recurrence intervals and slip rates, have been identified. The most serious threat comes from the Porters Pass Fault, which crosses through both lakes. Work carried out on this fault, along with other faults in the area, has shown that most of them are capable of generating large earthquakes with magnitudes of M7 or greater. The greatest threat from a more distant fault to all of the lakes in this study comes from the Alpine Fault, which is capable of producing a M8 earthquake.

Lake Tekapo is situated within a region that has historically, experienced a lower level of seismicity compared to other parts of New Zealand. Nevertheless, a number of significant faults occur in the vicinity of the lake, with the Alpine Fault situated c. 60 km away. The closest active faults to Lake Tekapo are the Forest Creek Faults, the Fox Peak Faults and Irishman Creek Fault Zone, all of which are capable of generating earthquakes of M7 or greater (Figure 7.5). A few other active faults, such as the Tekapo River Fault, also occur very close to the lake, but their seismic properties have not yet been identified.

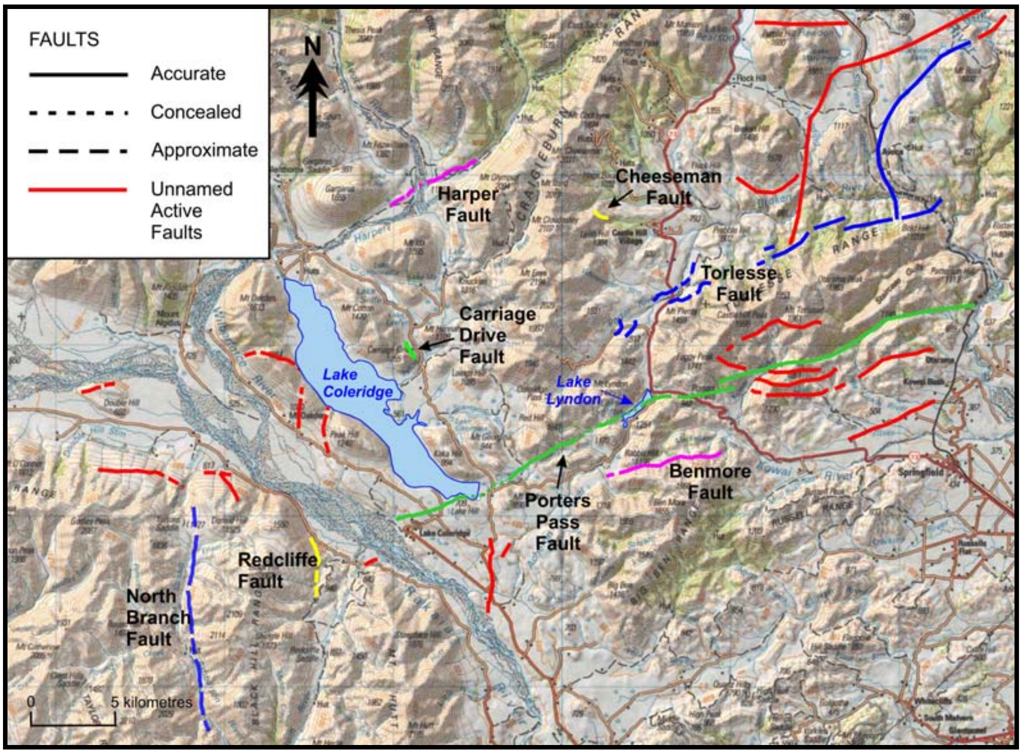

Figure 7.4: Local active faults within 15 km of Lakes Lyndon and Coleridge.

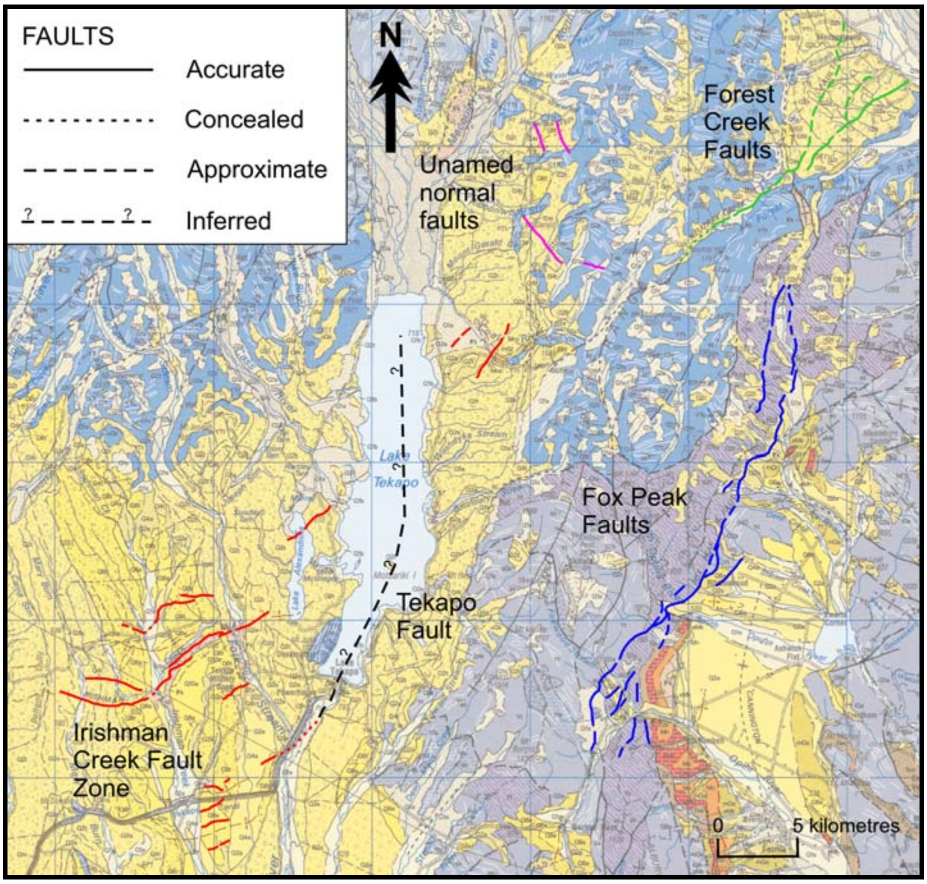

Figure 7.5: Local active faults within 15 km of Lake Tekapo.

There are a number of effects of earthquakes, including ground shaking, liquefaction, landslides, tsunami and seiches, which can have potentially disastrous consequences to a region. Ground shaking is the most widespread and prominent effect of earthquakes and has the potential to cause severe damage to lifelines and infrastructure. A new series of probabilistic seismic hazard maps produced by Stirling *et al.* (2007) depict the ground shaking intensities expected throughout Canterbury for given return periods. The maps show that intermediate ground conditions (shallow soil) around Lakes Lyndon and Coleridge will experience shaking intensities of MM7 in a 50 year period. The shaking intensities will most likely increase to MM8 for 150 and 475 year return periods and will reach a maximum intensity of MM9 for a 1000 year return period. However, there is likely to be a variation in levels of ground shaking around the lakes, as ground conditions are not all the same. Figure 7.6 illustrates areas likely to experience an increase or decrease in shaking compared to the probabilistic maps.

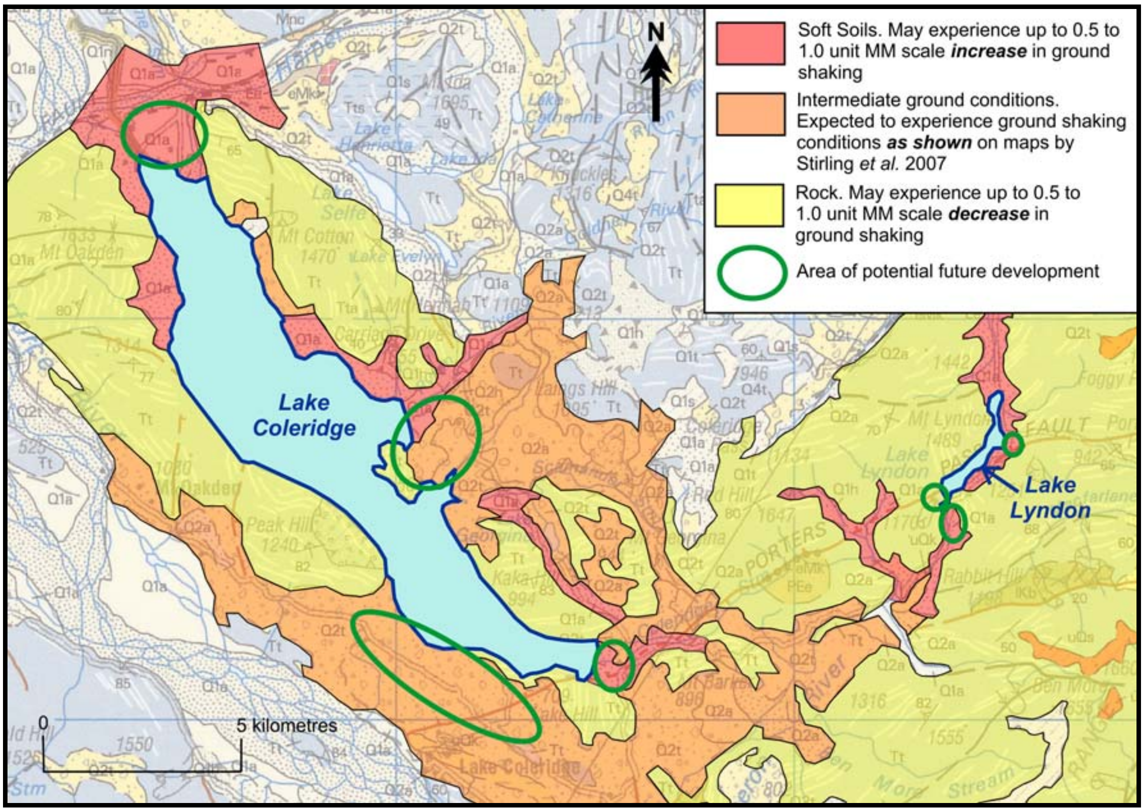

Figure 7.6: Ground shaking zones and areas of potential future development around Lakes Lyndon and Coleridge.

The areas likely to experience the greatest levels of shaking around Lakes Lyndon and Coleridge are those areas composed of Holocene alluvium and these areas are highlighted in red. These maps do not, however, consider topographic amplification of seismic waves. Ridge areas within the ‘rock’ (yellow) areas may then experience shaking intensities similar to those of ‘soft soil’ (red) areas. A summary of MM shaking intensities within these ground shaking zones is provided in Table 7.1.

Table 7.1: Expected MM shaking intensities within ground shaking zones around Lakes Lyndon and Coleridge.

Return Period	‘Red’ Soft Soil Areas	‘Orange’ Intermediate Ground Conditions	‘Yellow’ Rock Areas
50	7.5-8	7	6-6.5
150	8.5-9	8	7-7.5
475	8.5-9	8	7-7.5
1000	9.5-10	9	8-8.5

The probabilistic maps indicate that intermediate ground conditions around Lake Tekapo will experience shaking intensities of MM6 in any 50 year period. The shaking intensities will most likely increase to MM7, MM8 and MM8/9 for a 150, 475 and 1000 year return period, respectively. Likely variations in ground shaking based on geological assemblages that differ from intermediate ground conditions are shown in Figure 7.7. The areas likely to experience greater levels of ground shaking compared to the probabilistic maps are areas composed of Holocene alluvium and these areas are highlighted in red. A summary of these findings is provided in Table 7.2.

Liquefaction is another effect commonly associated with earthquakes. There is not a huge threat of this occurring around the lakes, but there are a few places with more potential for liquefaction occurring than others. The areas with the most potential for liquefaction occurring around the lakes are the red (soft soil) areas in Figures 7.6 and 7.7. Earthquakes are also capable of generating tsunami and seiches within the lakes, which threaten low-lying areas around each lake.

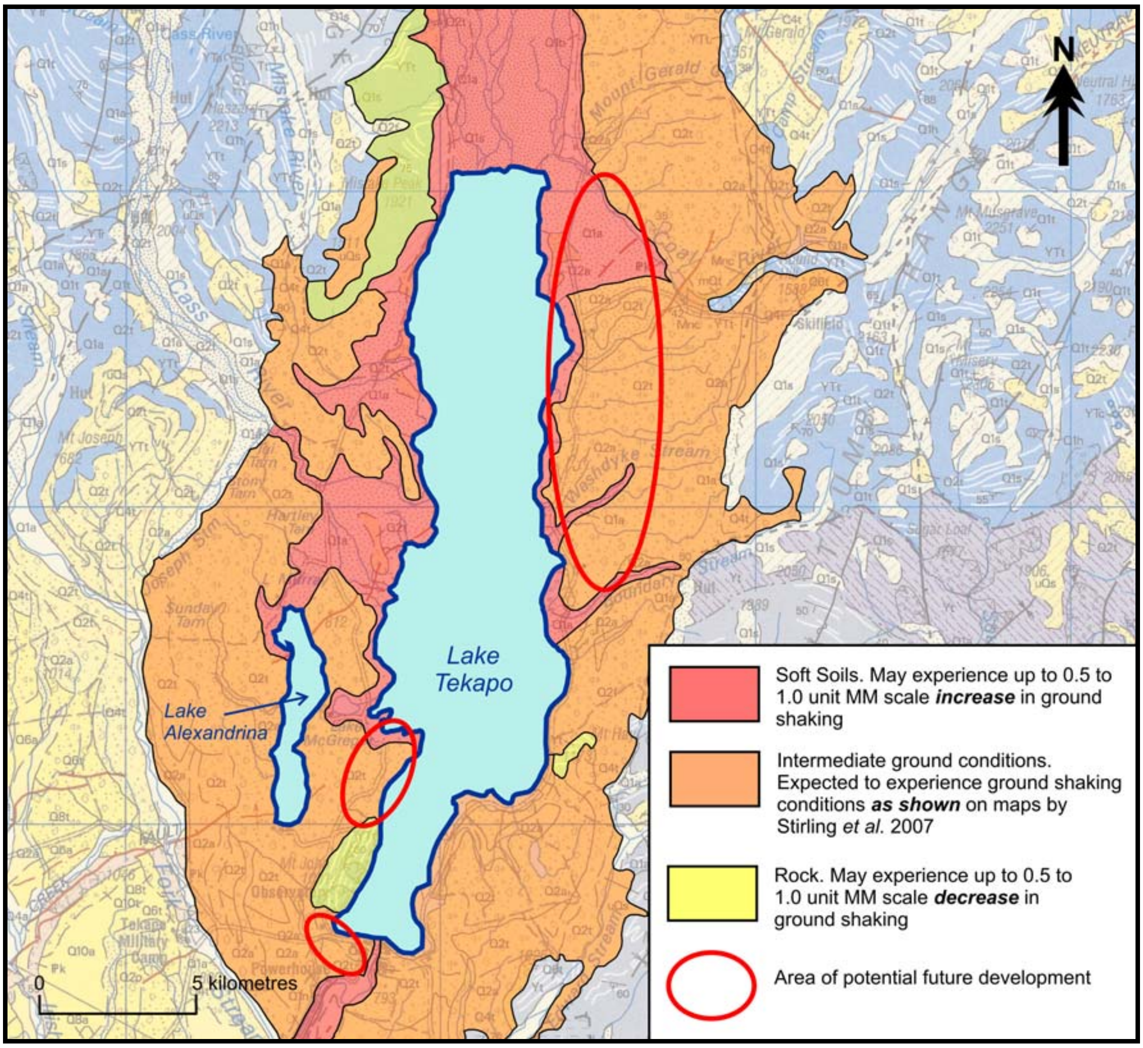

Figure 7.7: Ground shaking zones and areas of potential future development around Lake Tekapo.

Table 7.2: Expected MM shaking intensities within ground shaking zones around Lake Tekapo.

Return Period	'Red' Soft Soil Areas	'Orange' Intermediate Ground Conditions	'Yellow' Rock Areas
50	6.5-7	6	5-5.5
150	7.5-8	7	6-6.5
475	8.5-9	8	7-7.5
1000	8.5-10	8/9	7-8.5

7.3.2 Landslides

Landslides are common within the landscape around the Canterbury lakes. In alpine terrane, which is characterised by hard rock and steep, high slopes, landslides are dominated by rock avalanches, rock slides, rock falls and debris falls. Due to their volume, speed and potential travel distance, many alpine landslides are considered catastrophic and are responsible for death and destruction in populated regions of the world. Lakes Lyndon, Coleridge and Tekapo are all in part, surrounded by alpine terrane and as areas such as these become more populated, the potential hazard from landslides increases. Injuries, fatalities and property damage can occur directly from landslide impact of from indirect measures, such as flooding from a landslide-generated tsunami or from a landslide dam outbreak. The two main triggers of landslides in New Zealand are earthquakes and heavy rainfall.

A number of significantly large landslides have occurred in the vicinity of Lakes Lyndon and Coleridge within the last 10,000 years, including the Craigieburn Rock Avalanches, the Lake Coleridge Rock Avalanches and the Acheron Rock Avalanche. Fortunately, no large events have occurred in the last 150 years, but given the surrounding topography of the lakes and the regional seismicity, the likelihood of future large events is high. There have also been a number of slope failures identified within and around Lake Tekapo. At least fifteen mass movement deposits have been identified on the lake floor and a few rock avalanches have occurred at the head of the Godley River, the most recent being the Mount Fletcher Rock Avalanches.

The majority of slopes around Lakes Lyndon and Coleridge are at significant risk of earthquake-induced failure under moderate to strong earthquake shaking (i.e. MM intensities of MM 7 or greater) (Figure 7.8). As mentioned earlier, MM7 shaking intensities are expected to affect this area in any given 50 year period, making the threat from landslides to the area very high. One particular slope, Peak Hill, is of concern. It has been identified as being affected by some form of gravitational slope movement and if this slope were to collapse during earthquake shaking, it could cause significant waves within the lake, which may threaten opposite low-lying areas, such as the Ryton Bay area. Other slopes of concern include the Harper Fan and other subaqueous slopes, which have the potential to collapse and generate tsunami. If landsliding were to occur from the slopes on either side of the Ryton River, the Ryton River could be dammed, therefore, threatening development downstream.

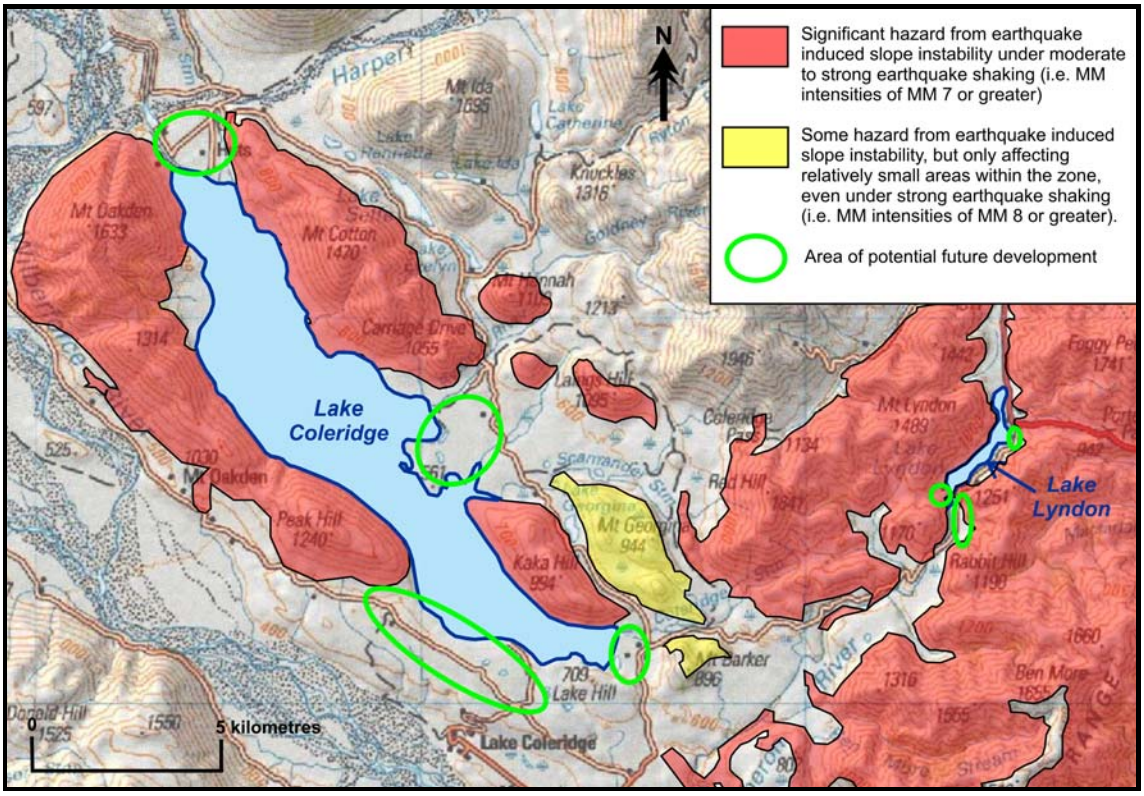

Figure 7.8: Potential earthquake induced slope instability zones around Lakes Lyndon and Coleridge. Boundaries are approximate only.

The majority of steep slopes around Lake Tekapo also have a significant risk of earthquake-induced landsliding during moderate to strong earthquake shaking (i.e. MM intensities of MM 7 or greater) (Figure 7.9). This area is expected to experience this level of shaking about once every 150 years. Currently, the development around the lake is concentrated at its southern end. The main threat to the development in this area comes from Mount John, which appears to have two sections affected by gravitational slope movement. This is of particular concern due to new development occurring at the base of this slope. If failure were to occur, a few million cubic metres of material could potentially be activated. Apart from Mount John, the other major areas of potential slope instability are the north-western mountains and the Godley River delta, all of which are capable of producing waves which could adversely affect the low lying part of the Richmond freehold area.

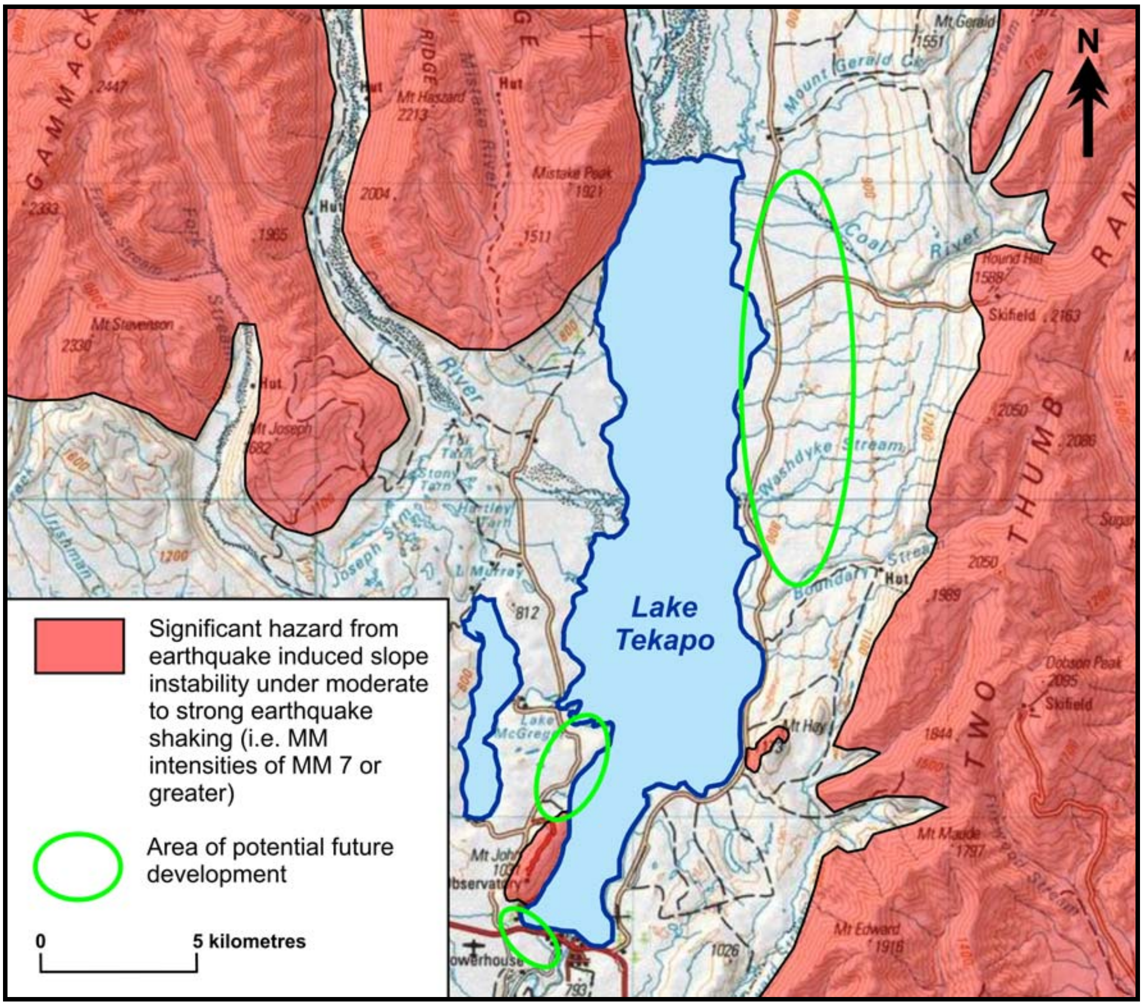

Figure 7.9: Slopes around Lake Tekapo at significant risk from earthquake-induced instability under moderate to strong earthquake shaking. Boundaries are approximate only.

7.3.3 Climate

New Zealand's long and narrow form, mountainous terrain and maritime setting, make the country particularly vulnerable to climate hazards. Climate hazards occur when the climate conditions of an area depart from normal to such an extent that people, property and social systems may be adversely affected. Canterbury is subject to extreme weather events, including high winds, drought, heavy snowfall and heavy rainfall, which can lead to a number of effects, such as flooding and landslides. Consequences of climate hazards include death and injury to people and livestock, structural damage to infrastructure and lifelines, and isolation of regions.

Lakes Lyndon and Coleridge have a climate of extremes, with conditions inclined to change rapidly. The area is prone to extremely strong winds, snowstorms and floods. Lake Tekapo also has a climate of extremes and is prone to high winds, heavy snowfall, heavy rainfall, droughts and flooding. The areas surrounding the lakes are not only susceptible to flooding from the lake itself but also from flooding in the rivers that feed the lakes.

7.3.3.1 Climate Change

Globally and locally, climate has changed significantly over geological time-scales. Temperatures have been increasing for the last c. 20,000 years, and what is of immediate concern is that within the last few decades alone, there has been an almost unprecedented rapid global warming trend. Climate change due to global warming is likely to have major and potentially irreversible effects at global and local scales on both the environment and human lives. Future climate change is most likely going to affect patterns of frequency and magnitudes of extreme weather events, leading to an increase in climate hazards. As most natural hazards are influenced either directly or indirectly by climate, the potential effects on lakeside development are of concern. Projected climate changes for Canterbury include:

- An increase in temperature of between 0.5 to 3.4ºC by the 2080s relative to 1990,
- Fewer cold temperatures,
- More high temperature episodes,
- An increase in rainfall in the Canterbury Ranges and a decrease in the plains,
- Heavier and more frequent rainfall for areas projected to have an increase in average rainfall (i.e. the Canterbury Ranges),
- Reduced snow cover, shorter seasonal snow lying, snowline rise and glacier retreat,

- An increase in severe wind, and
- Increased stormy conditions

An increase in the magnitude and frequency of rainfall events in the Canterbury Ranges will lead to an increase in the magnitude and frequency of floods, which is of particular significance to lakeside properties. Areas previously considered relatively safe from flooding may become more at risk and the vulnerability of development located on floodplains or next to shorelines may increase. As extreme rainfall events are a major cause of landslides, an increase in the frequency and magnitude of landslides will also most likely occur within the lake areas. The areas around the lakes most susceptible to climate hazards and their consequences, are low-lying areas (within c. 10 m of the lake level) next to the lakes or rivers and also areas next to landslide-prone slopes.

7.4 Natural Hazards and Areas of Future Potential Development at Lake Lyndon

There are a number of natural hazards that threaten areas of future potential development around Lake Lyndon (Figure 7.10). The first potential area is a relatively flat piece of land to the north of the lake, which topographically, appears suitable for development. However, this area is underlain with Holocene alluvium, which may be susceptible to local liquefaction. The area is also relatively low-lying (within 10 m elevation of the lake level), making it susceptible to flooding from an increase in the level of the lake.

There are two more relatively flat areas to the south of Lake Lyndon, which are also topographically suitable for development. The first area (number 2 in Figure 7.10) is located on an alluvial fan, to the south-west of the lake. Alluvial fans are often susceptible to future erosion and deposition processes, and for this reason alone, development should not occur here. The slopes surrounding the fan are also at significant risk from earthquake-induced instability under moderate to strong earthquake shaking. The largest threat to this area comes from the Porters Pass Fault, which is inferred to cross through the fan. A rupture event along this fault would most likely induce severe ground deformation in this area. The low-lying areas of the fan (within 10 m elevation of the lake level) may also be susceptible to flooding from the lake. Overall, this area is threatened by a number of natural hazards and should be kept free from development.

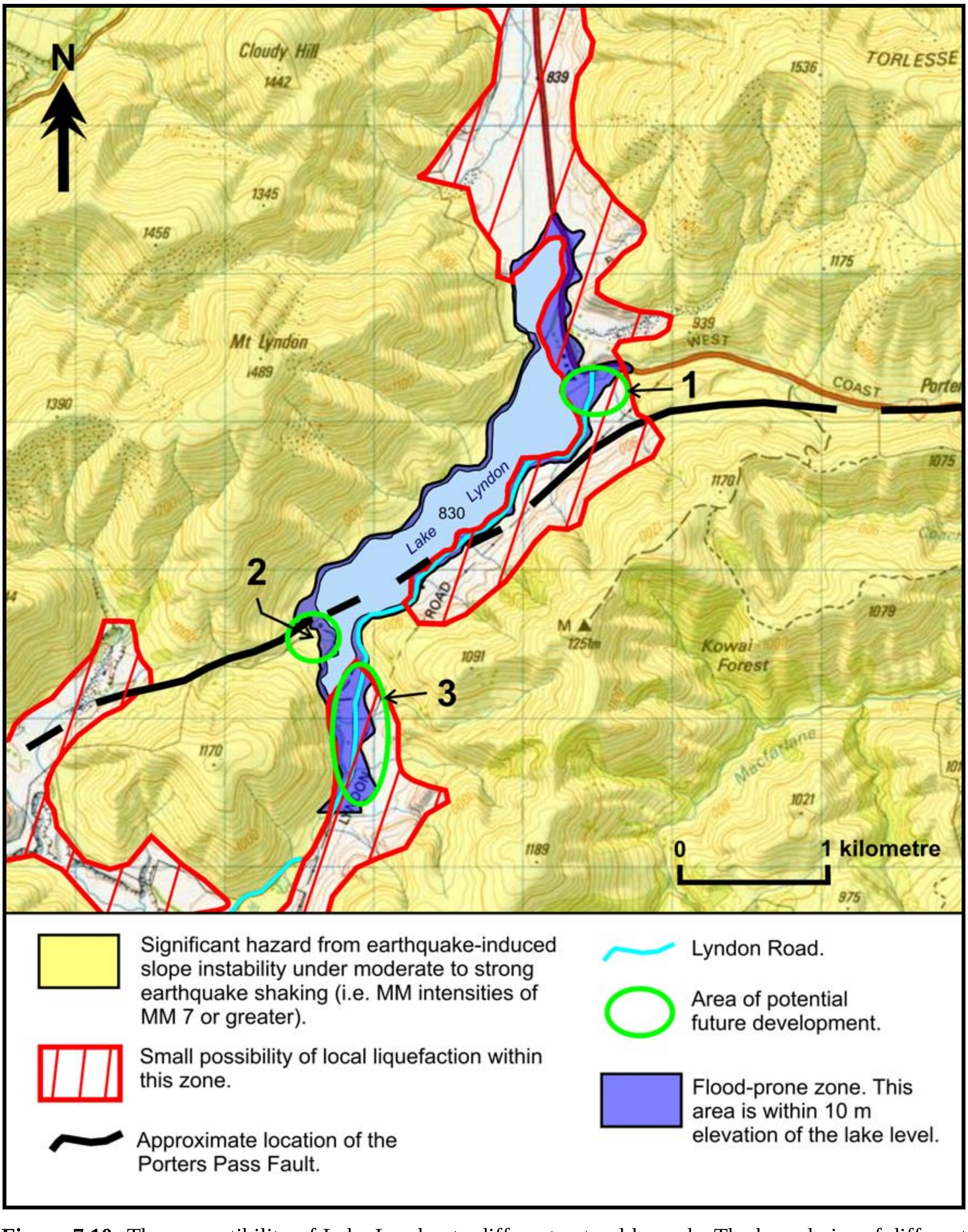

Figure 7.10: The susceptibility of Lake Lyndon to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

The third area (number 3 in Figure 7.10), which lies south of the lake, is also threatened by a few natural processes. The area is underlain by Holocene alluvium deposits, which may be susceptible to liquefaction during an earthquake. The area is also within 10 m elevation of the lake level, making it susceptible to future flooding. The slopes surrounding this area are prone to instability during moderate to strong earthquake shaking.

Each area around Lake Lyndon, which appears to be topographically suitable for development, is at significant risk from a number of natural hazards. The most significant threat come from the Porters Pass Fault, which crosses right through the lake. The Porters Pass Fault is an oblique, strike-slip fault, which is capable of generating M7.4 earthquakes. With each rupture event, the fault has previously moved, on average, c. 5.5 to 7 m. This is a significant amount of displacement and could cause a lot of damage to any development in the area. An earthquake along this fault is also likely to trigger a large number of landslides in the area. Therefore, due to the potential effects of earthquakes and landslides in the area, development should be avoided.

7.5 Natural Hazards and Areas of Future Potential Development at Lake Coleridge

There are four main areas around Lake Coleridge with future development prospects. The first area is the Harper Fan, at the lake’s northern end in between Mount Oakden and Cottons Sheep Range (Figure 7.11). This whole area is very low-lying (within 13 m elevation of the lake level) and is susceptible to flooding from an increase in the level of the lake, and also from the Harper and Wilberforce Rivers. The area is also flanked by steep ranges, which are at substantial risk of failing during moderate to strong earthquake shaking. The lake margin of the fan area may also be susceptible to landsliding during earthquake shaking or other measures. Lastly, as the fan area is underlain by Holocene alluvium, it may also be susceptible to liquefaction. Therefore, due to the combination of potential hazards that threaten this area, development here is not advised.

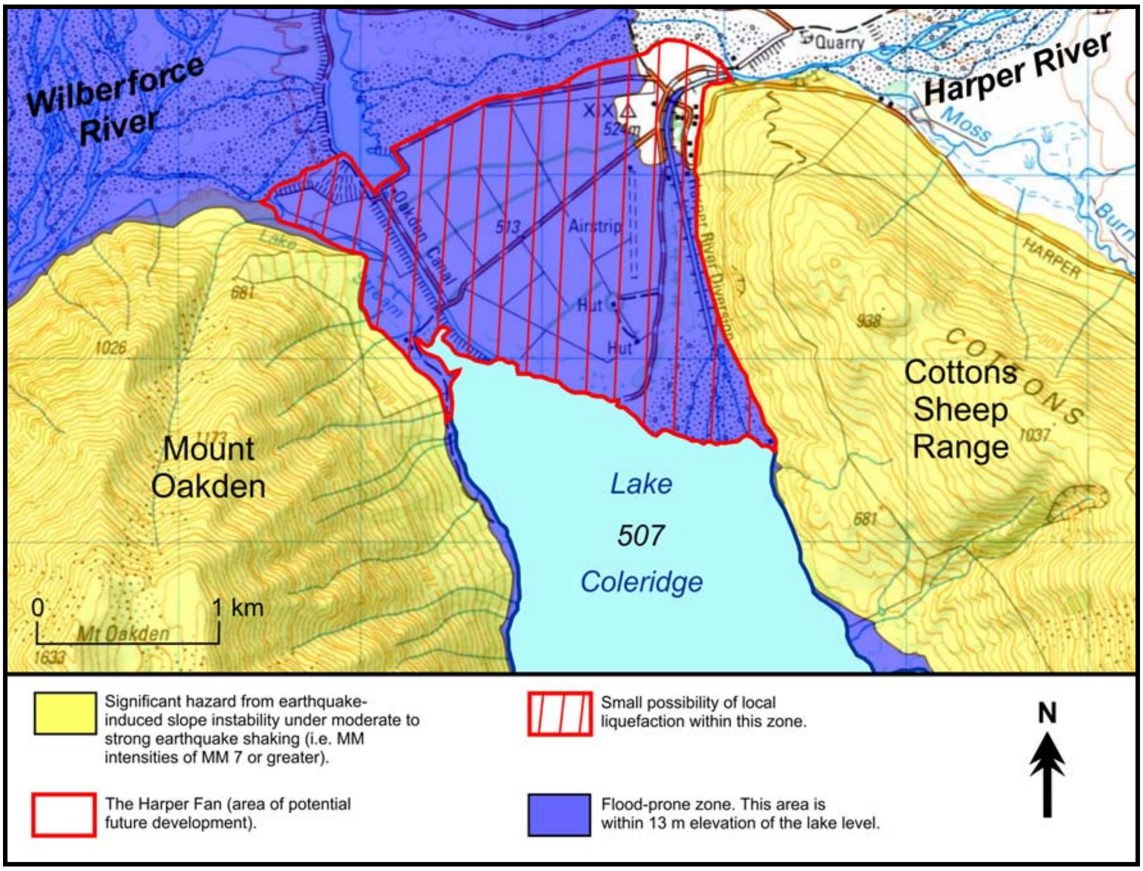

Figure 7.11: The susceptibility of the Harper Fan area to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

The second area of future potential development is along the north-eastern side of Lake Coleridge, between Carriage Drive and Kaka Hill (Figure 7.12). This area has incurred a lot of interest from developers. Most of this area is suitable for development but there are some areas, which should be avoided. For example, the low-lying area around Ryton Bay should not be developed. This is because it is the natural floodplain of the Ryton River and is within 13 m of the lake level. This, then, makes it susceptible to flooding from both the Ryton River and the lake itself. A number of rock avalanches are known to have dammed the Ryton River in the past, causing water upstream to pond and form a lake. Failure of these dams would most likely have led to extensive flooding in this low-lying area. As there is a significant hazard from earthquake-induced instability of the slopes surrounding the Ryton River today, the potential for further landslides blocking the Ryton River remains high. There is also a low possibility of liquefaction occurring here as this area is underlain by Holocene alluvium. Therefore, development along the north-eastern side of Lake Coleridge should take place on higher ground, such as the peninsula area to the south-east of Ryton Bay. It must be noted that the whole region is still susceptible to earthquake shaking and the effects of a possible landslide or earthquake-generated tsunami.

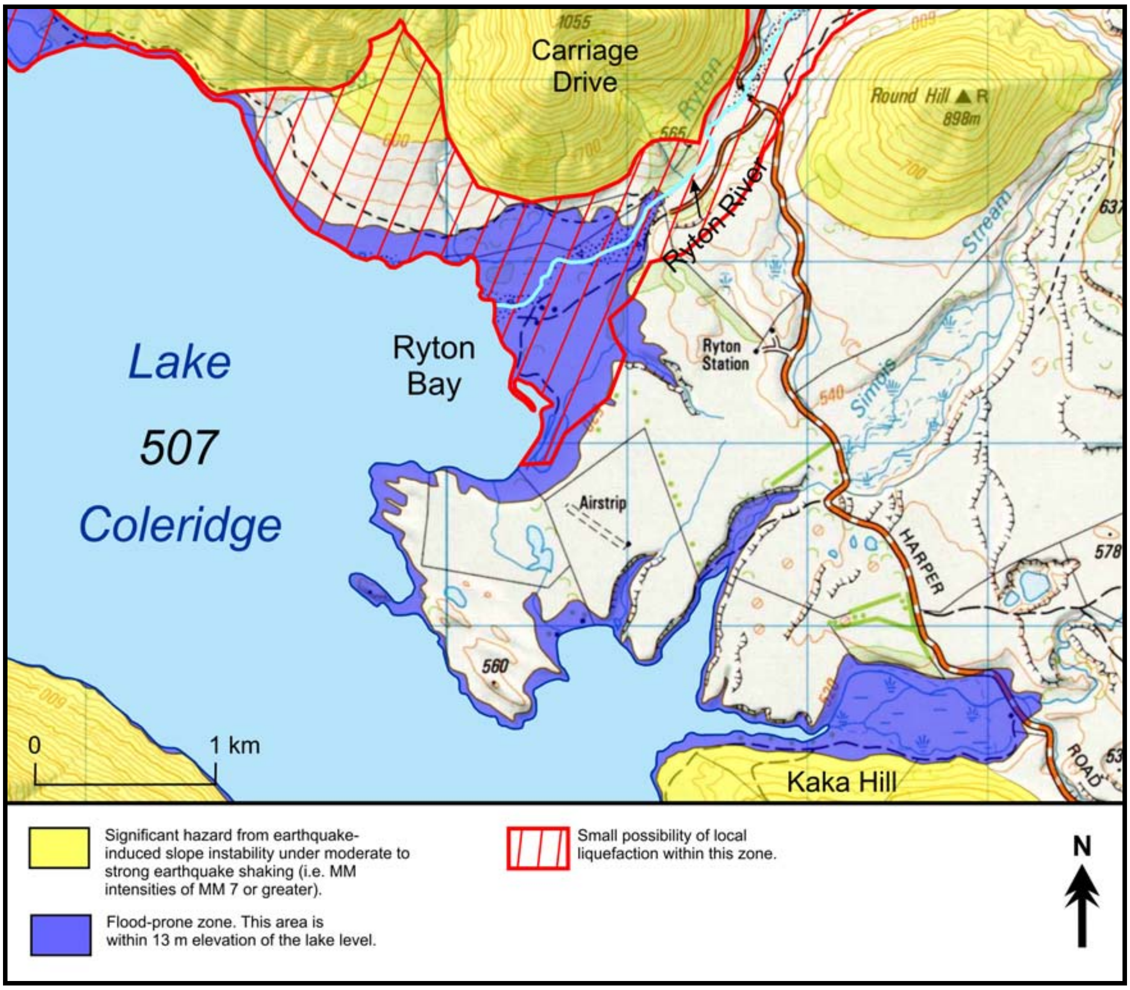

Figure 7.12: The susceptibility of the north-eastern side of Lake Coleridge to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

The third area with potential development prospects is around Lake Coleridge Station, at the lake's eastern most point (Figure 7.13). This area is prone to the effects of a number of natural hazards. Firstly, a lot of the area is relatively low-lying (within 13 m elevation of the lake level) and susceptible to flooding from the lake. Secondly, this area is also at risk from possible local liquefaction during earthquake shaking. However, this potential remains low. Most significantly, the Porters Pass Fault is inferred to cross right through this area. An approximate location of the fault trace is shown in Figure 7.13. There is also a high potential for surrounding slopes to fail during moderate to strong earthquake shaking. Due to this combination of hazards in this area, it is recommended that no further development take place.

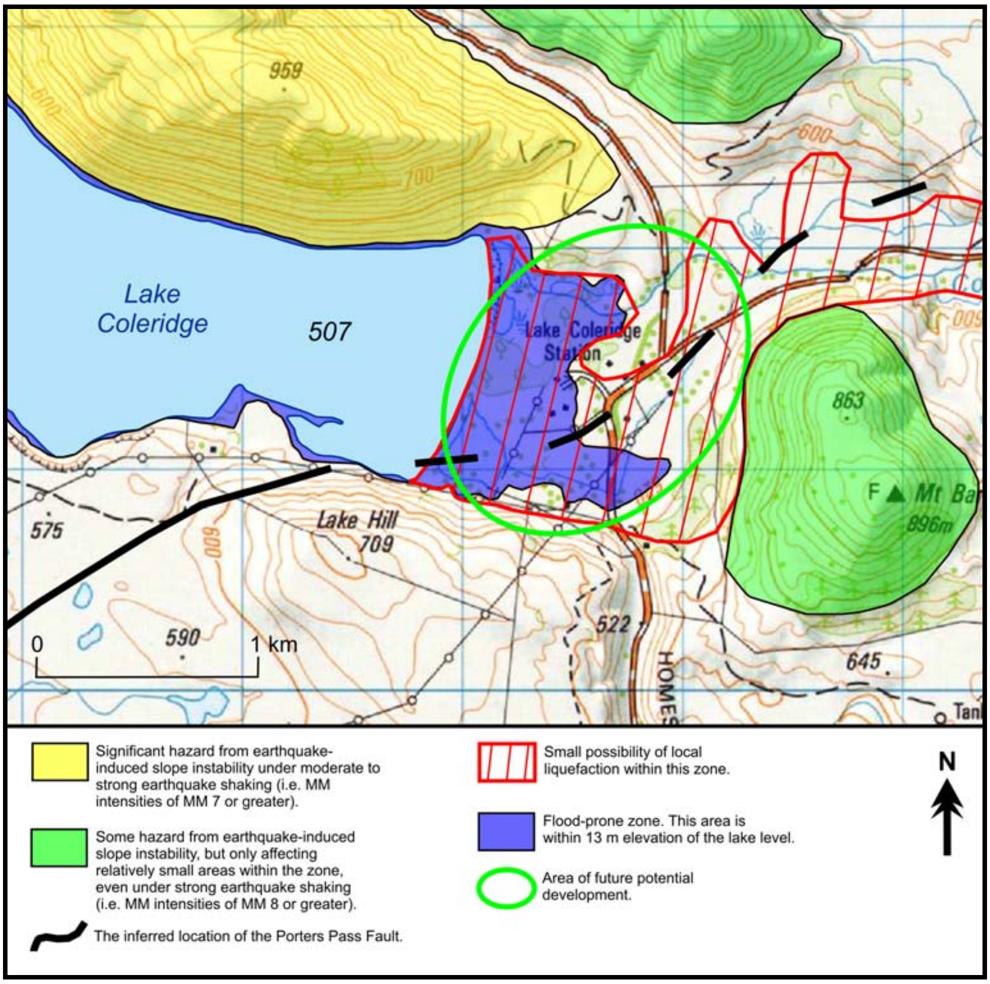

Figure 7.13: The susceptibility of the area surrounding Lake Coleridge Station to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

The fourth area with future development prospects is the land to the south of Lake Coleridge between Peak Hill and Lake Hill. The majority of this region is quite elevated with respect to the lake level, making it unlikely to be affected by flooding. The largest threat to the region comes from the Porters Pass Fault, which is inferred to cross through the eastern part of this section (Figure 7.14). According to planning guidelines by Kerr *et al.* (2003), the minimum buffer for safety in the area around an active fault is 20 m. This is because within 20 m either side of a fault is likely to be an area of intense deformation (ibid). Ideally, development should stay well away from active faults and therefore, should not occur to the east of the hydro-electricity tunnels.

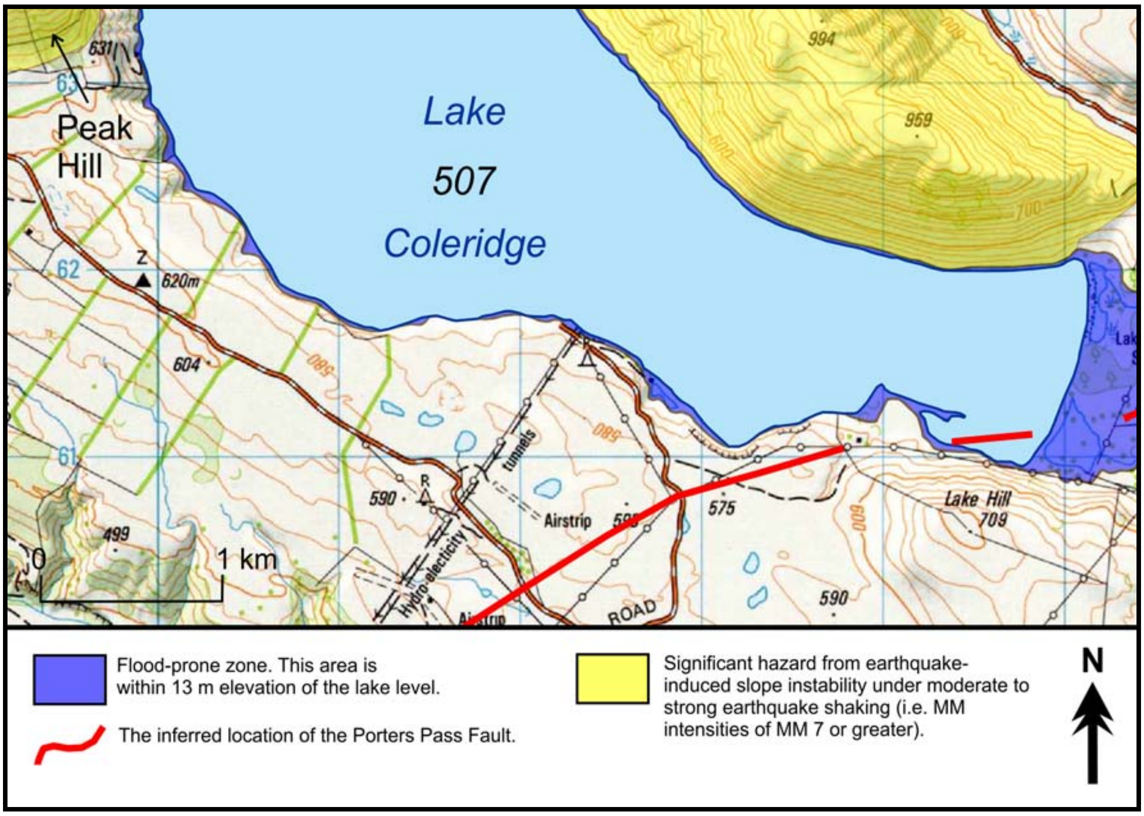

Figure 7.14: The susceptibility of southern side of Lake Coleridge to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

7.6 Natural Hazards and Areas of Future Potential Development at Lake Tekapo

There are three main areas around Lake Tekapo that have potential for future development. The first area is to the west of the current township at Tekapo (Figure 7.15). The low-lying coastal areas of this area are prone to flooding from the lake and should be avoided. However, the higher elevated areas behind the coastal zone appear suitable for development. There is the possibility of a large landslide from the southern side of Mount John, which could affect areas immediately at the base of this slope and low-lying areas. An active fault is inferred to cross right through the middle of the current township. However, the seismic properties of this fault remain unknown. Further work should be carried out on this fault to determine the risk it presents to this area. An appropriate buffer should then be placed around the fault to prevent development occurring in an area, which could undergo substantial ground deformation.

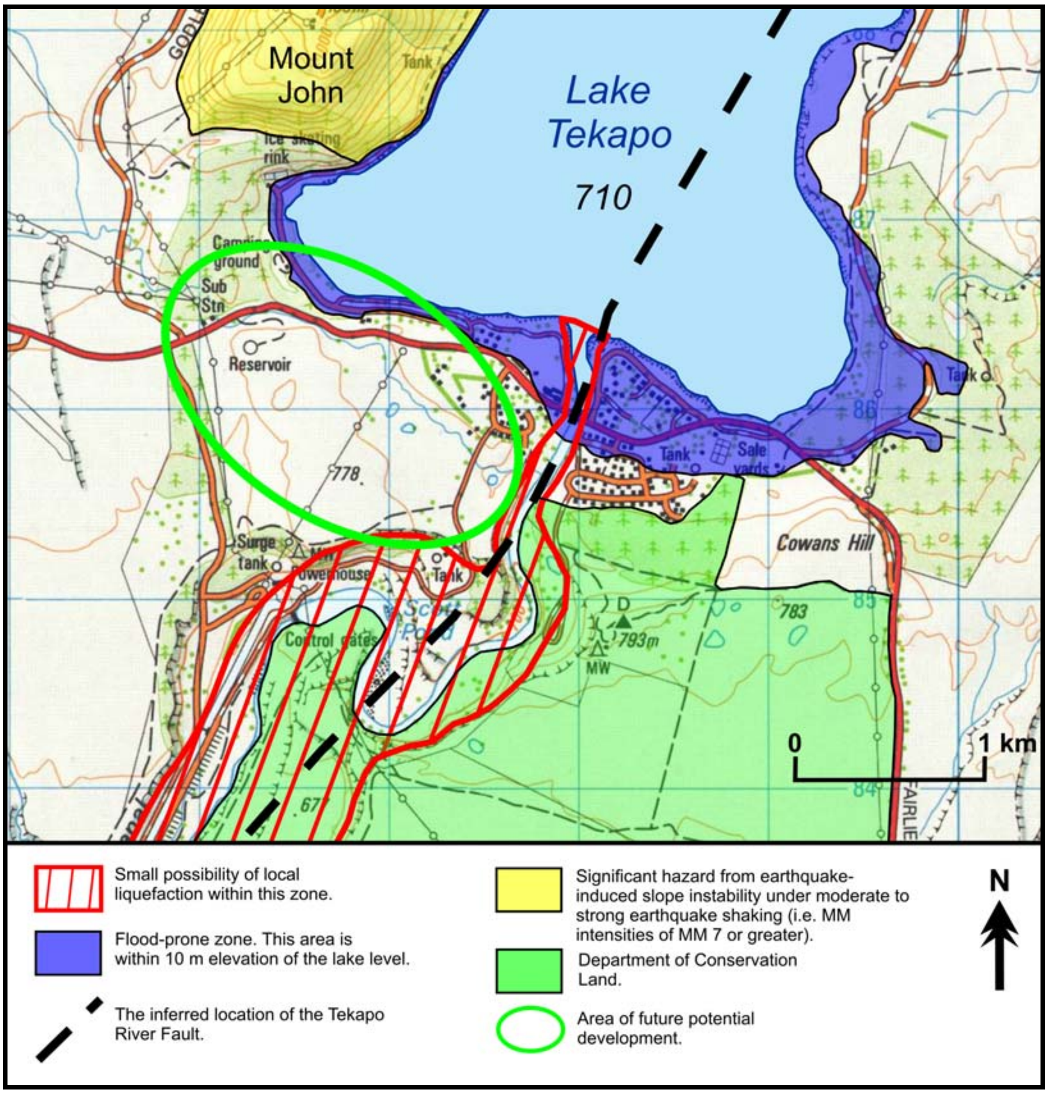

Figure 7.15: The susceptibility of the area west of the Tekapo Township to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

The second area with future potential prospects is the freehold section of Richmond Station to the north-east of Lake Tekapo (Figure 7.16). The majority of this area is suitable for development, but there are a few areas which should be avoided. The first of these is the floodplain of the Coal River. This area is susceptible to flooding from the river and may also be susceptible to local liquefaction. An active fault is also inferred to cross through the floodplain and another active fault is thought to be located to the east of the floodplain. However, the seismic properties of these faults have not been identified and it is not clear how much of a threat they present. Therefore, future work should be carried out to determine this. An appropriate buffer should then be established around the faults in order to avoid damage to future development.

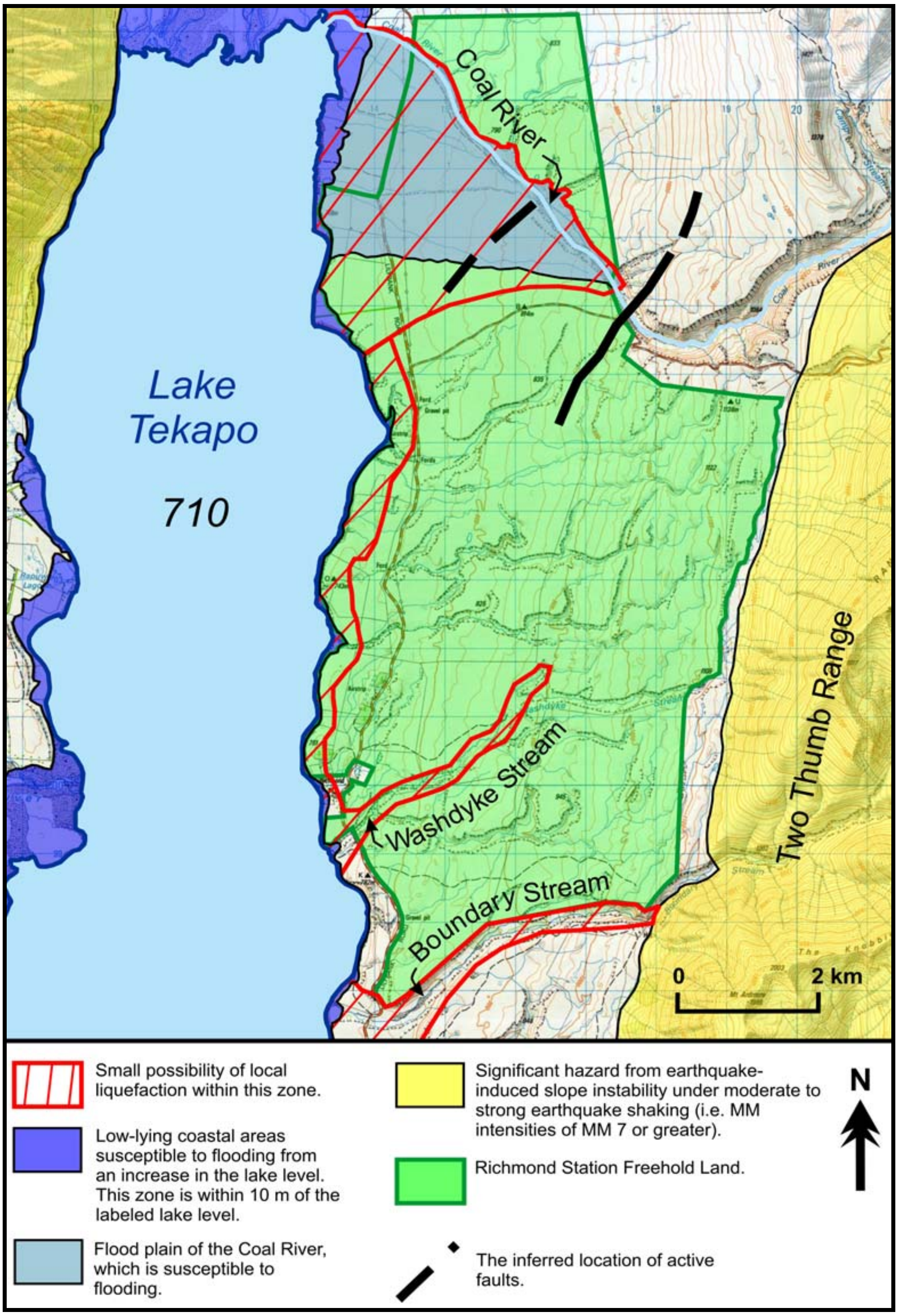

Figure 7.16: The susceptibility of the freehold section of Richmond Station to different natural hazards. The boundaries of different phenomenon shown on the map are approximate only.

The Two Thumb Range bounds the east of the freehold area. There is a high possibility of landsliding occurring along the range front during moderate to strong earthquake shaking. An appropriate distance should be kept between the range and future development. The coastal areas and stream courses underlain with Holocene alluvium have a low potential of liquefaction during earthquake shaking.

The third area with potential development prospects is the coastal area to the north of Mount John (Figure 7.17). Once again, low-lying coastal areas prone to flooding identified in Figure 7.17 should be avoided. These areas may also be susceptible to liquefaction. An appropriate distance from Mount John should also be kept, as there is a significant hazard from earthquake-induced instability of its slopes.

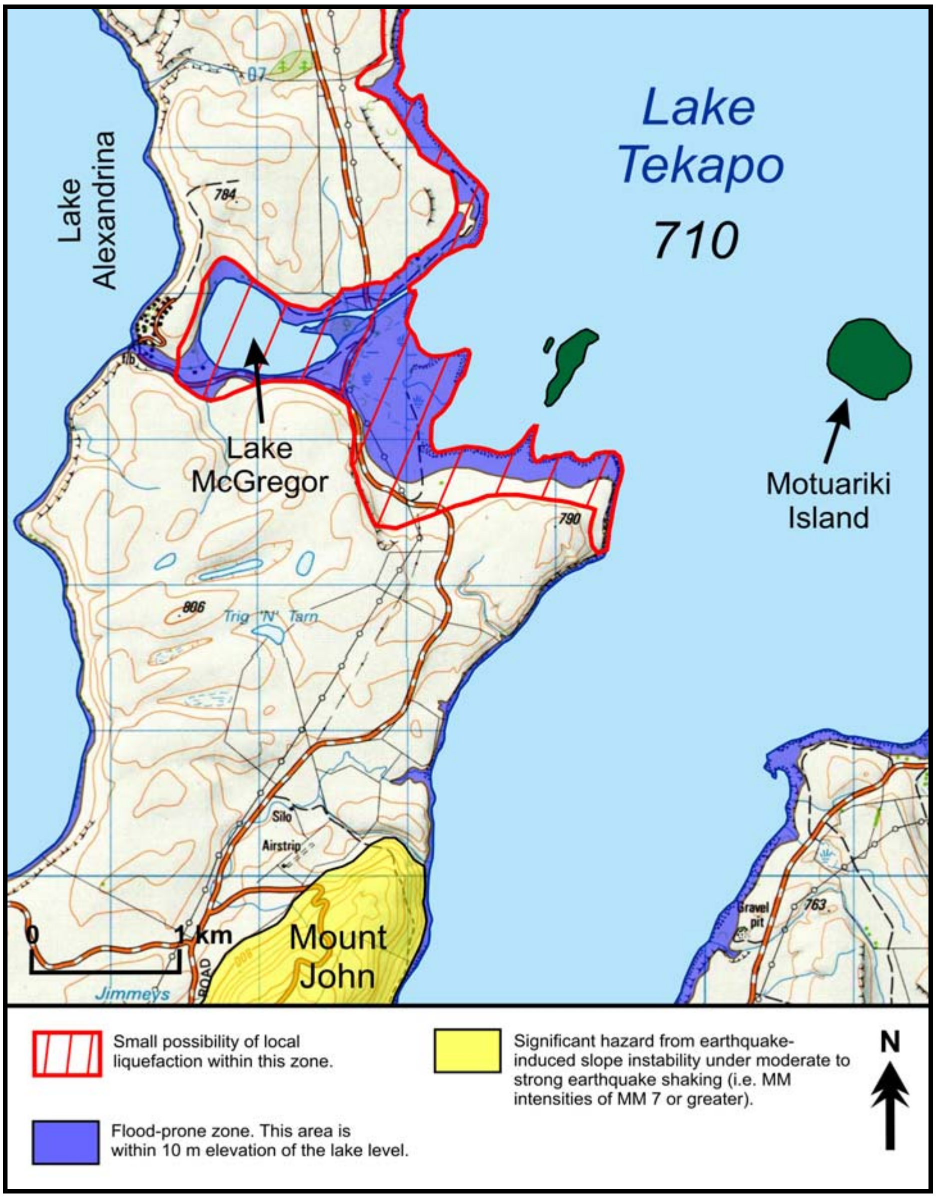

Figure 7.17: The susceptibility of the coastal area to the north of Mount John to different natural hazards. The boundaries of different phenomena shown on the map are approximate only.

7.7 Conclusion

There is not a lot of potential for development at Lake Lyndon. However, there is the possibility that some form of development closely linked with recreation or conservation purposes may be constructed. Upon investigation of possible development sites and the threat from earthquakes, landslides and climate hazards to these areas, it is advised that development at all locations around the lake be avoided.

There are four main areas of potential development around Lake Coleridge. Out of these four areas, two of them are suitable for development (the north-eastern and southern areas of Lake Coleridge). However, within these areas, there are certain parts, which should be avoided due to the threat from flooding, liquefaction, ground rupture and landsliding. The other two areas (the Harper Fan and Coleridge Station areas) should be kept free from development as combinations of hazards threaten the whole areas.

There are three areas around Lake Tekapo with development prospects. All three areas are, to some extent, vulnerable to ground rupture, landsliding, flooding and liquefaction but only in localised areas. Provided that these identified areas are avoided to an acceptable level, development in these areas is suitable.

This investigation into natural hazards and areas of development around Lakes Lyndon, Coleridge and Tekapo has been a reconnaissance study only. A more detailed investigation into each area should be undertaken before development occurs. In particular, the stability of certain slopes, such as Mount John and Peak Hill should be determined. Properties of active faults that occur in potential development areas, such as the Tekapo River Fault, should also be determined.

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